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Investigation of the suitability of a fused filament fabricated tool for incremental sheet metal forming

Dieter Weise[1]*, Christian Langner[1], Alexander Pierer[1], Verena Kraeusel[1], Jana Petru[2], Jiri Koziorek[2], Michal Prauzek[2]

[1] Fraunhofer Institute for Machine Tools and Forming Technology IWU, Reichenhainer Strasse 88, 09126 Chemnitz, Germany.
[2] VSB – Technical University of Ostrava, 17 Listopadu 2172/15, 708 00 Ostrava-Poruba, Czech Republic.

Abstract

Incremental sheet forming (ISF) is a flexible manufacturing process for sheet metal parts in small to medium quantities. Successive movements of a stylus create the geometry of the sheet metal part. ISF can be performed with or without a counter tool. By using counter tools, the geometry deviation of the formed sheet metal part can be reduced. To achieve the broader application of ISF, counter tools must be cost-effective, fast, and individually producible, even for batch sizes of only one part. In addition to milling, which has been the main method used to date, additive manufacturing (AM) also makes it possible to meet these requirements for flexible counter tool production. To investigate the suitability of AM for the production of counter tools for the ISF and to learn more about the load on the counter tool, a cylindrical counter tool made of polylactic acid (PLA) was produced using the fused filament fabrication (FFF) process. This counter tool was used for the ISF of drawing steel. Based on the force measurement results, a first step towards suitability evaluation of 3D-printed counter tools for ISF was taken, and possibilities, as well as application limits for such counter tools were discussed.

Keywords: incremental sheet forming, rapid tooling, additive manufacturing

1. Introduction

Incremental sheet metal (ISF) is a forming process in which the sheet metal is formed step by step through multiple, successive movements of a stylus until a final part geometry is achieved. The ISF is in particular characterized by a stylus with a low degree of shape memory. This allows for the flexible manufacturing and modification of parts. The ISF is divided into different process variants. There are processes with and without a counter tool. Single Point Incremental Forming (SPIF) is the variant with one stylus on one side of the sheet and no counter-tool on the other. The absence of a counter tool leads to much greater flexibility in forming but has the disadvantage of lower accuracy than other ISF processes. Processes with either partial or full counter tools are referred to as Two Point Incremental Forming (TPIF) (Langner, 2022).

In TPIF, a machine tool or a robot arm with a clamped stylus is used to form sheet metal into its final part geometry via predetermined paths. On the opposite side of the sheet metal, there is a counter tool which entirely or partially reproduces the shape of the part. In the case of partial support, the sheet is held

*Corresponding author: dieter.weise@iwu.fraunhofer.de
ORCID ID's: 0000-0002-6828-0278 (D. Weise), 0000-0003-1881-8989 (A. Pierer), 0000-0002-0293-7898 (V. Kraeusel), 0000-0002-2378-5678 (J. Petru), 0000-0002-7138-887X (J. Koziorek), 0000-0003-1348-1328 (M. Prauzek)

against unwanted deformation only at relevant points, in order to be able to guarantee shape accuracy there. In contrast, with a complete counter tool, the sheet is supported from the second side at every point during forming. This ensures greater forming accuracy.

The sheet metal is always held at the edges (usually by means of clamping frames) for forming. Since the process is only used for small quantities due to the high process time, the counter-tools can also be made of plastic and wood. Rieger et al. (2017) have taken advantage of the approach of the counter-tool consisting of plastic and have manufactured it additively using the fused filament fabrication (FFF) process via a robot with an extruder unit. A second robot then presses a sheet metal to this counter tool with a stylus and thus reshapes the sheet metal (Rieger et al., 2017). The sheet is clamped only once in the process, which shortens the processing time. This process is characterized by its high flexibility and by the short time from the CAD model to the finished sheet metal part.

To estimate the force required during the ISF process, Aerens et al. (2010) developed a formula that can be used to approximately predict the force acting in the z-direction. In their series of experiments, 77% of the results did not deviate from the prediction by the formula by more than 15%.

The acting forces in ISF have already been studied in various experimental setups (Kumar et al., 2019). For example, Li et al. (2017) simulated and evaluated an FE model using LSDyna with fine-volume elements. This work investigated the forming forces on AA7075-O sheets using a DLNC-PC machine from the Amino Corporation. The results showed that the axial force gradually increased to a maximum value of 2200 N in the initial forming phase. Azevedo et al. (2015) studied the effects of different lubricants on the forming forces of steel (DP780) and aluminum (AA1050-T4) on a SPIF-A machine. Here, the maximum forming forces in the axial direction of the forming tool were 1500 N for DP780 and 330 N for AA1050-T4. Chera et al. (2013) investigated the performance of Kuka industrial robots during the SPIF process in terms of forming forces. DC04 steel sheets with an initial thickness of 0.4 mm were used. The results showed that the maximum value of the force in the axial direction was 230 N.

Belchior et al. (2013) compared the forming forces of an industrial robot with those of a three-axis milling machine on an AA5086-H111 sheet with an initial thickness of 1 mm. The results showed that the forming force of the computerized numerical control (CNC) milling machine was 30% higher than the force generated by an industrial robot. Thus, 900 N was applied with the robot and 1200 N with the CNC milling machine (Belchior et al., 2013; Mohammadi et al., 2016).

Mohammadi et al. (2016) also investigated the effects of different heat treatment conditions using a six-axis industrial robot on AA2024-T3 sheets with an initial thickness of 0.4 mm. The forces were up to 380 N with heat treatment and up to 200 N without heat treatment. Honarpisheh et al. (2016) investigated the influence of the infeed increment on Ti-6Al-4 V sheets at a temperature of 400–500°C using the ISF method experimentally and numerically. The forming forces were 800 N, 1300 N and 1500 N for the feed increments of 0.1, 0.3 and 0.5 mm. Li et al. (2017) measured the forces occurring during ISF in the axial direction on 0.5 mm thick Al1050-O sheets, investigating the force differences between tests with and without the use of ultrasound. It was found that these forming forces were lower with the use of ultrasonic technology.

However, very few investigations have been carried out on the TPIF process to analyze the forming forces because of the complexity of the experimental setup due to the use of partial or full counter tools (Kumar et al., 2019).

2. Methodology

2.1. Experimental setup and experimental part

For the ISF tests, the 5-axis portal milling machine type MIKROMAT 30V 5D (DYNAPOD) was used (Fig. 1a). The test machine tool is particularly characterized by its high rigidity. The tool holder had been modified on this multifunctional machine tool so that a stylus could be clamped in place of a milling tool. This stylus (Fig. 1b) can roll on sheet metal. A stylus with a diameter of 30 mm was used for the experiments.

The clamping frame was specially designed and manufactured for forming tests with generatively manufactured tools (Fig. 2a). With this clamping frame, it is possible to form sheets in an area of 300 mm × 300 mm. Sheets of up to 350 mm × 350 mm can be clamped. In addition, a forming depth of up to 50 mm is possible. A fixture with anti-rotation protection is provided in the center of the clamping frame. For the counter tool, a partially supporting cylinder counter tool was selected. This has a diameter of 70 mm and is provided with a dedicated fit at the underside for mounting on the clamping frame. The upper edges are rounded with a radius of 5 mm.

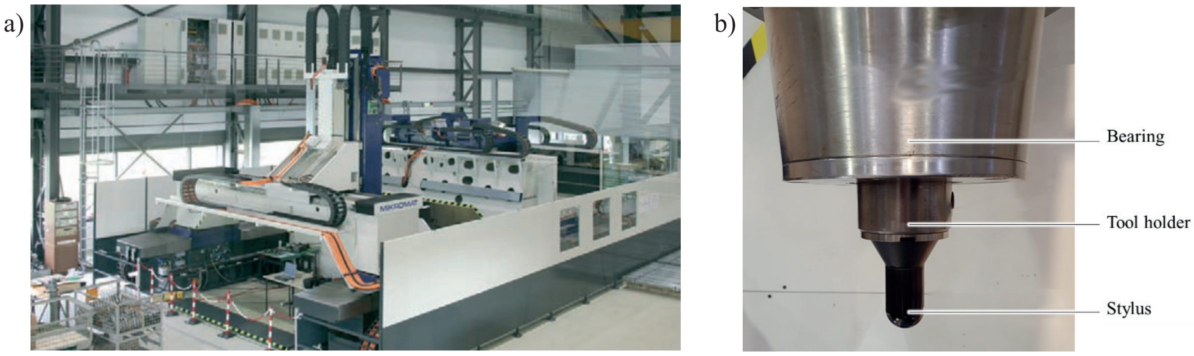

Fig. 1. Universal machine tool DYNAPOD at Fraunhofer IWU Chemnitz (a) and a stylus in the tool holder (b) (Langner, 2022)

A Kistler type 9011A measuring washer (measuring range: 15 kN; preload 3 kN) was used as the force transducer. Kistler type 5011 charge amplifier was used in the measurement setup. The signal from the charge amplifier was forwarded to the IMC CRONOS-PL type A/D converter from IMC Messsysteme GmbH. The sensor's sampling rate was set to 100 Hz for the experiments.

Since the blankholder is not movable, the sheet metal must always be formed inside as well as outside. The test geometry (Fig. 2b) was created on the basis of the counter tool. The upper circular surface of the counter tool has a diameter of 70 mm and is also provided with the same radius at the edges as the counter tool. This radius is only increased by the thickness of the sheet during forming. The forming angle is 45°, and the forming depth is 48 mm (Fig. 2c).

The test material is DIN 1541 DC04 sheet steel, which was developed for cold forming and therefore has high formability. The tensile strength Rm of up to 350 MPa is low for steel. The material used also has a low yield strength $R_{p0.2}$ of 250 MPa. The initial sheet thickness t_0 for the test geometry presented is 0.5 mm.

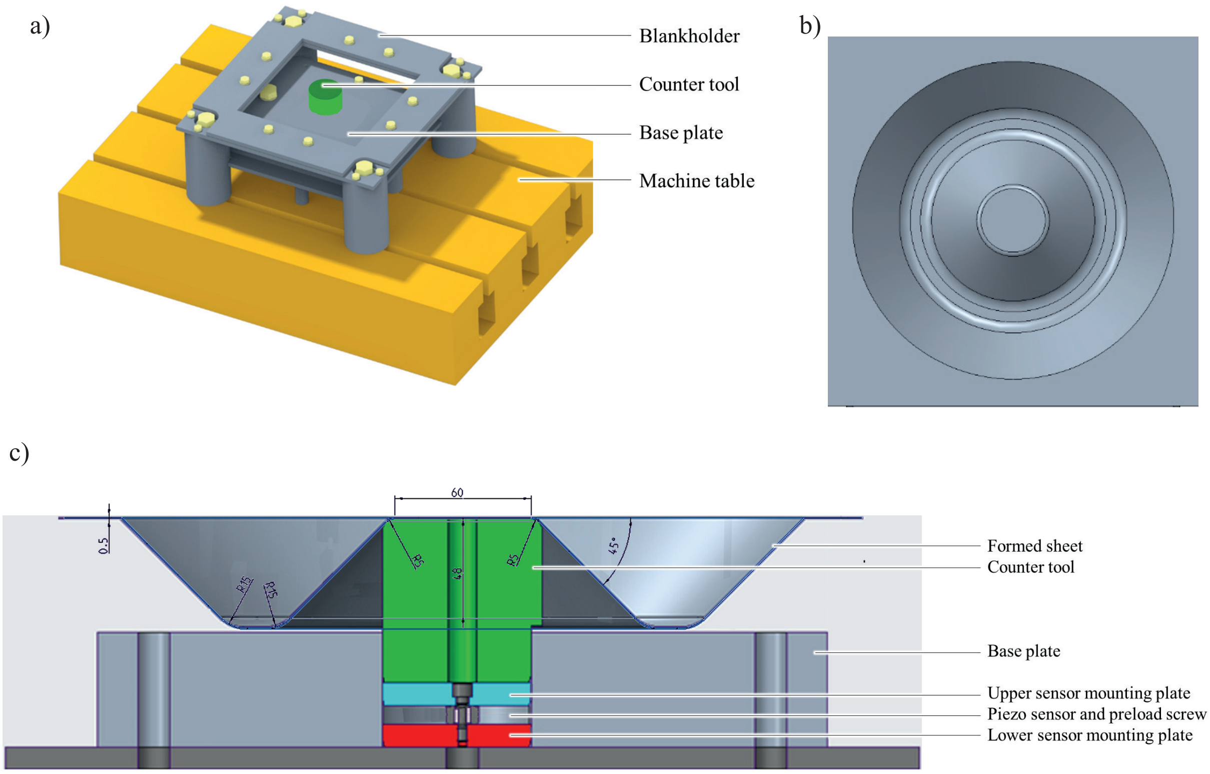

Fig. 2. Design of the test setup: a) setup as CAD render image (Klinger, 2022); b) CAD image of the experimental geometry from the top view; c) sensor installation in the recording in the CAD cross-section

2.2. Experiments and experimental results

For the force estimation, 3 tests were carried out with the material described. No geometric changes could be measured on the counter tool (initial state to final state after the tests). To rule out possible differences in the individual measurements due to the rolling direction, the sheets were always inserted in the clamping frame so that the rolling direction was always parallel to the *y* coordinate axis of the machine. For the tests, the sheet was first formed on the outside and then on the inside per plane. The paths of the tests were taken at a path speed of 5 m/min and a distance in the *z*-direction between the paths of 0.5 mm. Forming the partially supported cone shape (Figs. 2 and 3) of 48 mm in the *z*-direction took 30 min 58 s for each of the three experiments.

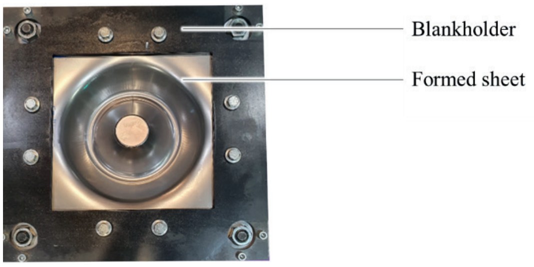

Fig. 3. Formed sheet in forming setup

The force was measured over the entire test period at a sampling rate of 100 Hz. The measured values for the force in the *z*-direction (Fig. 4) were in a similar range for all three tests. For example, the maximum value for the measured force in the first test (B1) was 1258 N. The second test (B2) resulted in a force in the z direction of 1258 N. The second test (B2) resulted in a maximum force of 1293 N, and the third test (B3) resulted in a maximum force of 1288 N. Furthermore, the respective maximum force per path decreases after 960 s. This occurs until the second 1440, after which the maximum force per lane increases again. The maximum standard deviation over the three experiments was 259.6 N. The average standard deviation over the entire test time was 10.79 N. This can be attributed to process-related fluctuation and is within a normal range.

In area A (Fig. 5), the force input during the outer forming path is only in the range of a few Newtons. However, a sharp increase in force was recorded during forming the inner path. The first small peak occurs when the stylus is fed into the sheet. After this, the force drops briefly as the stylus remains in this position for a short moment until it starts moving again in the forming plane. Thereafter, the force increases to the largest peak for this one forming path. At the end of the path, the force drops again and is then in the range of a few newtons.

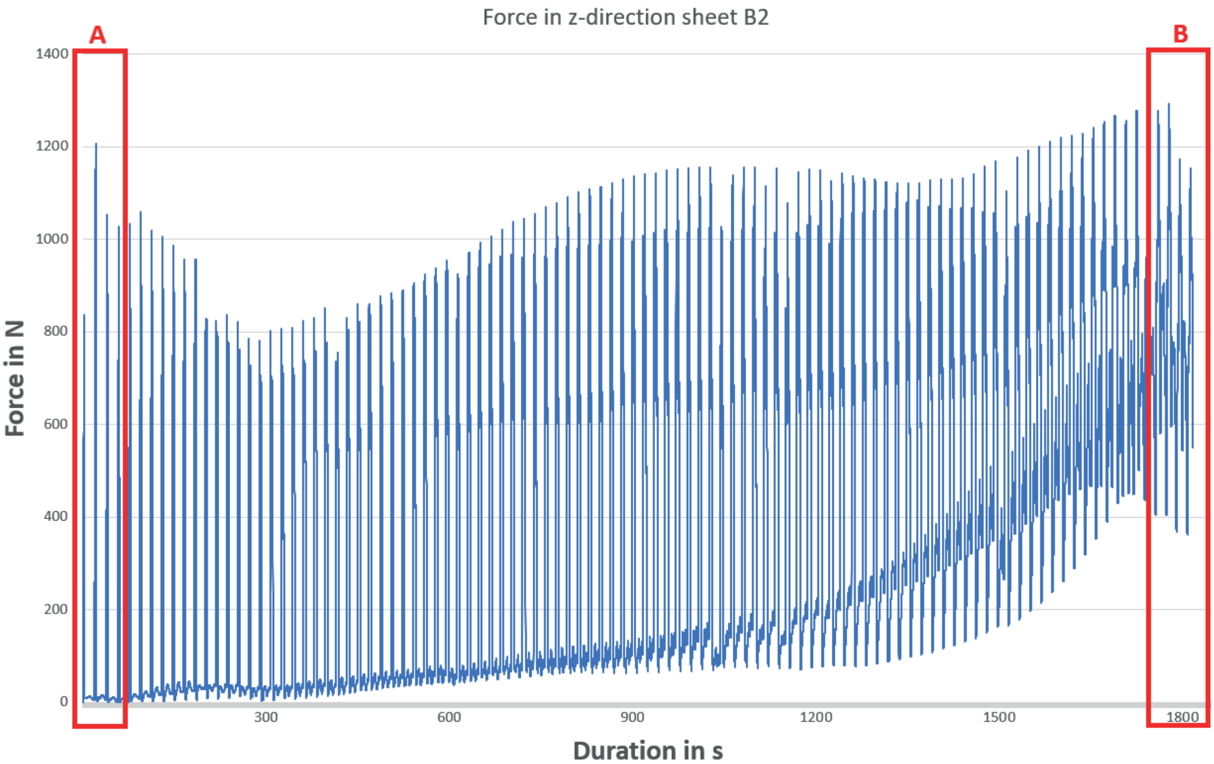

Fig. 4. Force in *z*-direction for sheet B2 over the complete test duration

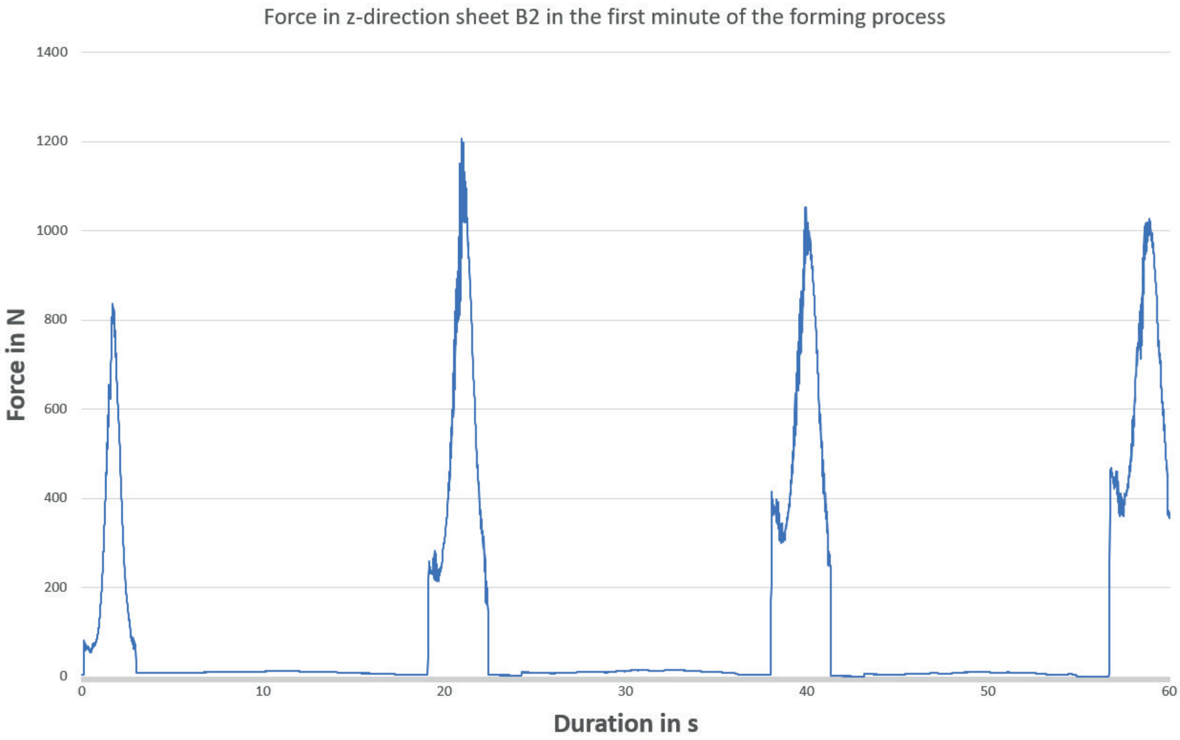

Fig. 5. Forces in z-direction in the 1st minute of the forming process (A)

Figure 6 shows area B from Figure 4. It can now be seen that the greater the forming depth, the greater the force on the counter tool during forming of the outer geometry. In this section, forces of up to 900 N are reached. The forces of the inner geometry reach their maximum value of between 1250 N and 1300 N in this section.

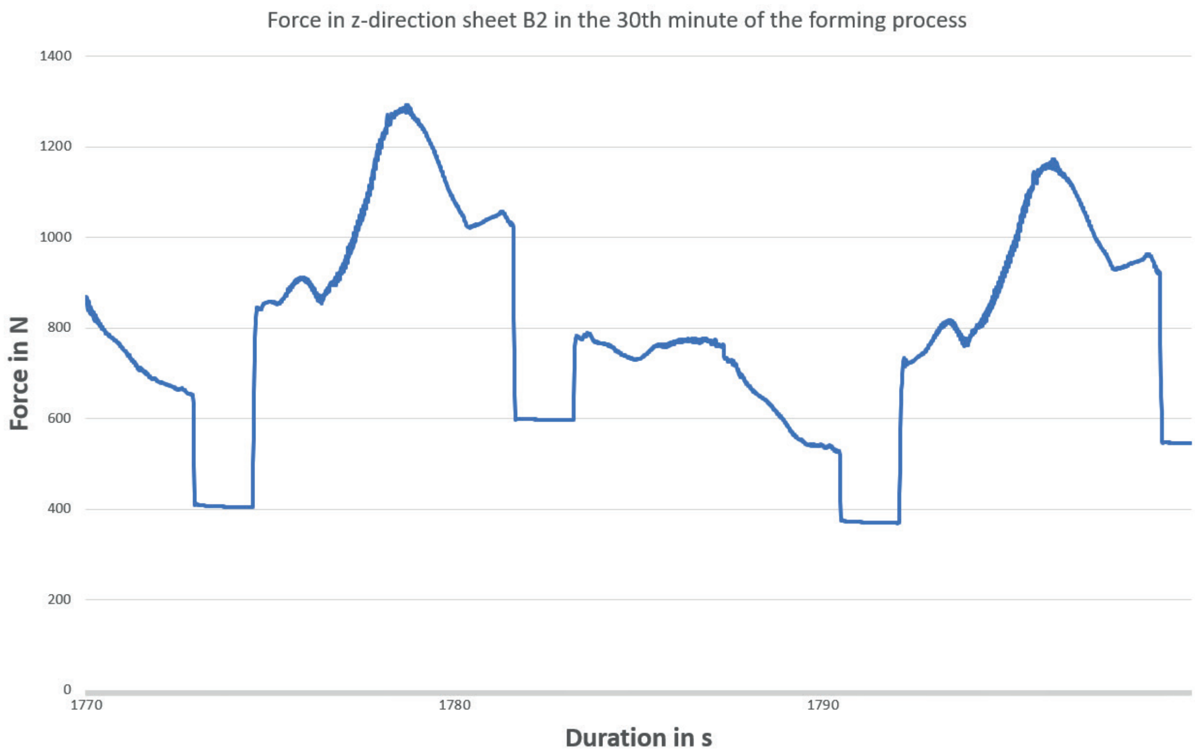

Fig. 6. Forces in z-direction in the 30th minute of the forming process (B)

3. Discussion

The forces measured in the tests were qualitatively and quantitatively very similar from one sheet metal part to the next. This is also documented by the average standard deviation. It allows the conclusion that the test conditions and the test setup did not change significantly during the tests, which is important because the ISF focuses on producing small quantities. The measured forces show that the force depends on the duration/distance covered by the stylus after an infeed movement, the distance to the part center and the forming depth. Low forces were recorded at the outer clamping edge of the sheet, especially at the start of forming, because the forces introduced by the stylus were absorbed to a large extent by the sheet clamping. The force input on the counter tool was greatest when the sheet was formed in the last planes. Furthermore, it was also possible to show how small the influence of distant forming areas at the start of forming was on the centrally located counter tool. In this case, a SPIF process was operating, which should lead to the fact that the forces were applied to the counter tool and the sheet support to a similar extent.

4. Conclusions

Testing the suitability of additive, FFF-printed counter tools was a major driving force for the conducted investigations. Based on the results of the presented experiments, it is thus assumed that, in principle, 3D-printed counter tools can be used for the ISF. Thus, the measured maximum values of below 1300 N can be used on the one hand as a reference for the counter tool design and, on the other, also for the blank holder design. Furthermore, the newly generated knowledge about the geometry-dependent force values allows a force-dependent counter-tool design. Investigating the extent to which forces can be reduced with modified feed rates and further lift-off and infeed movements is therefore an aspect to be investigated in the future. Furthermore, the force measurement in the area close to the sheet metal clamping represents an interesting target for follow-up investigations.

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