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Development of polygon forming processes for aerospace engineering

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Abstract. The focus of this research lays on the further development of the Polygon Forming Technology, which is already successfully used for cold forming components in the aerospace industry. One example is the fuselage shell of the Airbus Beluga XL. According to the current state of the art it is possible to incrementally form large cylindrical or conical fuselage components by Polygon Forming. With the use of so-called infills, the Polygon Forming process can also be used to form components with pockets milled in the initial plane state. The limits of this technology exclude the creation of spherical geometries, such as those used in the front or rear fuselage sections of aircrafts. Presently, such components are produced by more complex stretch forming processes, which result in a considerable amount of scrap. In this work, a tool is developed to replicate the Polygon Forming process on experimental scale at the Institute of Forming Technology and Machines (IFUM) for materials commonly used in aerospace engineering. In addition, a downscaled pre-test tool is developed to investigate different tool geometries for incremental spherical forming inexpensive and easy according to the method of rapid prototyping.

Introduction

Since the mass of an aircraft has a decisive influence on fuel consumption, lightweight construction is of particular interest in aviation. Therefore, a reduction in weight has enormous economic and environmental benefits [1]. In addition to fiber-reinforced plastics and titanium alloys, mainly aluminum alloys are used due to their low density [2]. Various aluminum alloys come into operation in the aerospace industry. An application example for alloys of the 7xxx series is the use for highly stressed components in the fuselage structure [3]. Another alloy used for the production of fuselage parts is EN AW2024 - T351. Depending on the alloy, the mechanical properties such as strength or resistance to stress corrosion cracking can be adjusted with the aid of heat treatments. The respective conditions are defined according to DIN EN 515 [4].

To generate the desired geometries of the sheet metal parts, sheet metal forming processes are an essential technology in aircraft production [5]. The manufacturing of large-area fuselage structural parts in the aerospace industry is usually carried out by means of roll-forming or stretch-forming. Roll-forming is a process for the production of curved sheet metal parts. A possible design of roll-forming lines is a symmetrical three-roll arrangement [6]. This technology provides favorable loading conditions with comparatively low forces and is usually used for forming thick plates [7]. In stretch forming, a flat sheet blank is usually clamped on two opposite sides and is then formed into the desired shape by the action of a forming punch. Depending on the punch geometry, stretch forming can also be used to produce spherical sheet metal components. However, this technology is associated with a high material waste, limited dimensional accuracy and an undesired reduction in sheet thickness [7]. Another method to produce aircraft fuselage parts is the incremental bending process Polygon Forming, developed and patented by the company Deharde GmbH [8]. Here, aluminum sheets are bent by means of incremental forming. According to DIN 8586, bending serves to plastically form solid components (e.g. metal sheets), whereby the plastic state is essentially generated by bending stresses [9]. Usually special machines such as presses, bending or straightening machines are used for this purpose [10]. Polygon Forming represents a special form, which is suitable for the production of curved, turned, and conical sheet metal parts, where relevant geometric elements, such as pockets, drill holes or recesses are generated before the bending process. This eliminates the need for time-consuming post-processing, which usually require cost-intensive five-axis milling machines.

In the cooperative joint project "Aggregated Polygon Forming based Processes for large Fuselage Components" (AgaPolCo) involving the Deharde GmbH and the IFUM, the technology of Polygon Forming, which has so far only been applicable to cylindrical and conical components, is to be transferred to the production of spherical components. Spherical components are mainly used in the front or backside area, while cylindrical components are mainly used in the middle area of aircraft fuselages (see Fig. 1). In order to make Polygon Forming usable for the new spherical use case, a tool with which the Polygon Forming process of Deharde can be reproduced on a hydraulic press at the IFUM is developed. The tool will be designed, built and set up. In addition, another downscaled prototype tool is used to investigate forming strategies and tool geometries for incremental spherical forming. The experimental investigation provides a preselection of suitable tool geometries. Here, the experimental investigation is faster than a numerical one due to the simulative complexity. The identified optimal tool geometries will be further optimized iteratively in the further course of the project by means of numerical investigations.

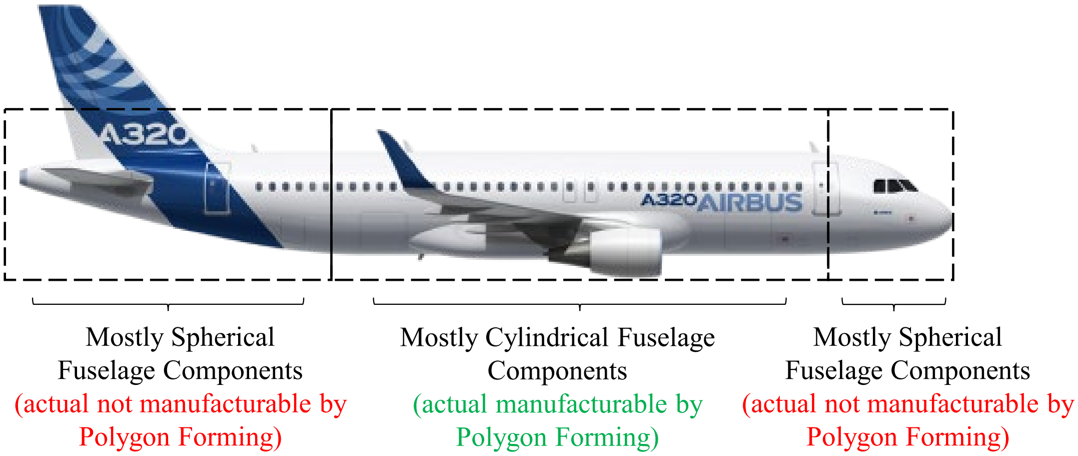

Fig. 1: Fuselage sections of an aircraft on the example of an Airbus A320 (image source: [11])

Materials and Methods

The overall aim of the project "AgaPolCo" is the production of spherical components by incremental bending from the aluminum alloy EN AW2024 - T351. For this purpose, a polygon forming demonstrator tool is built with which blanks are initially bent cylindrically and in the evolving project it is aimed to form spherically on a hydraulic press. EN AW2024 - T351, in the following named AA2024, is one of the most popular high strength aluminum alloys. Due to its high strength and fatigue resistance, it is commonly used on components and structures in aircrafts. AA2024 has a yield strength of approx. $R_{p0,2} = 290$ MPa and a tensile strength of approx. $R_m = 440$ MPa [12].

Tool geometries for bending spherical components are to be investigated in a preliminary testing tool. For this purpose, several tool concepts are additively manufactured using the rapid prototyping method. Since the tools are not printed in massive form to save time and costs, they cannot stand high forming forces. Therefore, a more ductile material than the high-strength AA2024 must be used for the forming experiments. The AlMg alloy EN AW5754, short AA5754, has a very high formability, which allows the production of components with complex geometries. It has a yield strength of approx. $R_{p0,2}$ = 80 MPa and a tensile strength of approx. R_m = 240 MPa [12] and is therefore taken as pre-testing material.

Scaled Polygon Forming Tool

Based on the forming tool of the company Deharde, a tool is designed with which Polygon Forming can be investigated at the IFUM. The tool can be installed in a hydraulic double-column press type HDZ400 of the company Dunkes GmbH. The basic tool consists of the active component sword and bed as well as one adapter each for installation on the machine bed and on the press ram (see Fig. 2). The sword is screwed interchangeably to the upper die and is pressed incrementally into the sheet blanks during the process. The bed serves as a support for the blanks and is designed to be adjustable in width. The sword and bed are made of polyamide (PA6) to ensure a certain elasticity in the contact and thus prevent imprinting contours on the blanks. Three layers of spring steel 1.1274 in the thickness of t = 1.5 mm are placed on the tool bed to provide a smooth ground for the sheet blanks and to enable the bending of the outer contour of the sheet. The sheet blanks are rectangular plates with a dimension of 500 mm x 500 mm and a thickness of t = 3.2 mm made out of aluminum alloy AA2024. The rolling direction of the sheets is oriented perpendicular to the feed direction.

Initial forming experiments are conducted to investigate the accuracy and reproducibility of the process. Therefore, the aluminum plates are manually fed step by step with a feed width (FW) of FW = 20 mm after each stroke perpendicular to the press ram movement. After each feed the sword is pressed path-controlled into the sheet plates up to an indention depth (ID) of ID = 0.8 mm beneath the bed surface. The bed width (BW) is set constant to BW = 110 mm. The experiments are repeated three times with these parameters.

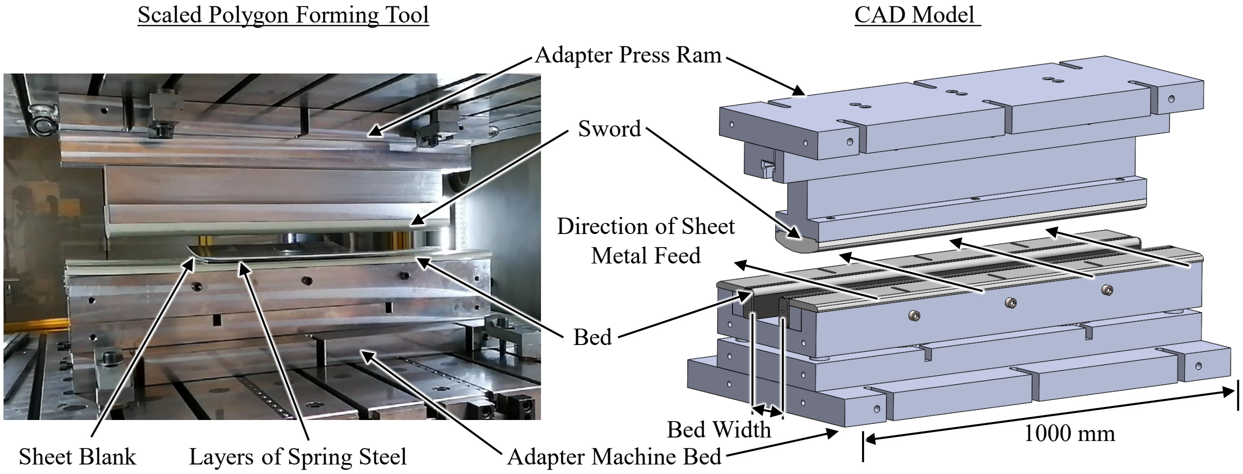

Fig. 2: Scaled Polygon Forming Tool at the IFUM

After incremental bending, aluminum plates are measured with an optical measuring device Atos 2 400 of the company Carl Zeiss GOM Metrology GmbH. The bending of the sheet plates is evaluated by determining the bending lines from the three-dimensional scan data. The bending lines are determined for each of the formed plates at five positions. Averaged bending lines are determined for the inside radii of the plates and compared with each other (see Fig. 3). A comparison of the three formed plates (Test 1-3 in Fig. 3) show, that the process provides a good reproducibility. The relative standard deviation of the three averaged inside radii is SD = 2.76 %.

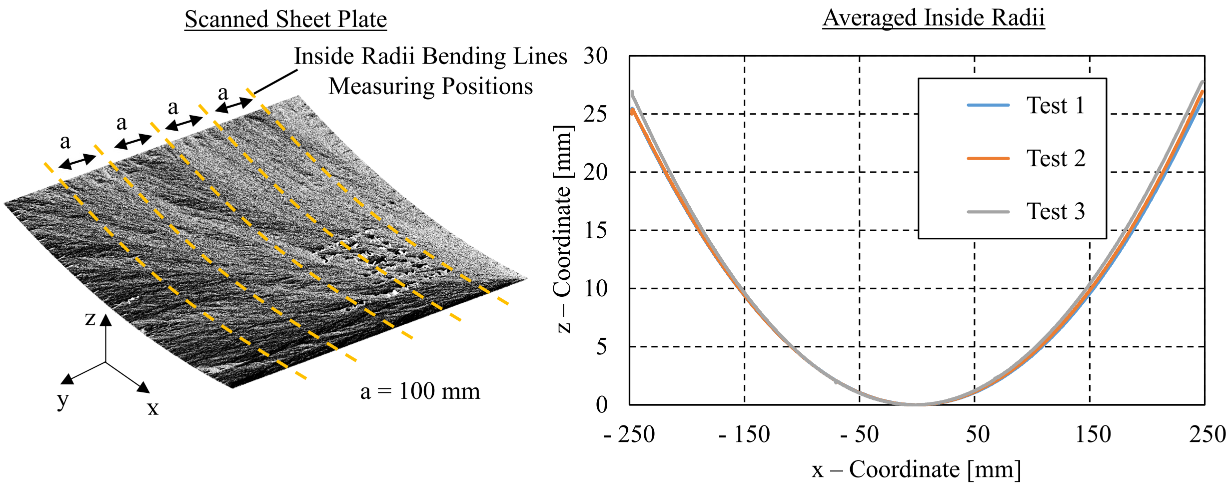

Fig. 3: Measurements of the profile bending of incremental formed cylindrical AA2024 plates

Therefore, the experiments show that the scaled Polygon Forming tool is suitable to reproduce and to analyse the Polygon Forming process executed on industrial scale by Deharde. In order to identify tool geometries for spherical forming, a pre-testing tool was developed.

Pre-Testing Tool

In order to identify suitable tool concepts for spherical forming, a preliminary experimental study is carried out in which various sword and bed geometries are investigated. Thus, the applicability of the developed concepts will be validated experimentally. For this purpose, different sword and bed variations are additively manufactured on a 3-D printer (type RF2000 of the company Conrad Electronic SE) and tested for spherical forming in a pre - testing tool on a manual press. The additively manufactured components are printed from the material polylactic acid (PLA) in segments, which are joined together to form total tool components (see Fig. 4). The segmental production is necessary because the 3D printer has a limited production space and the complete length of the components cannot be produced in one print.

The pre - testing tool consists of a sword which can be moved vertically along two guide profiles by means of sliding slides and return springs. The guide profiles are connected to a base frame from which the supports (bed) for the blanks extend. The sheets to be formed are placed on the bed and feed manually in after each stroke. The forming force is applied via a hydraulic punch, which can be moved to a fixed indentation depth (see Fig. 4 left). As plate material AA5754 in the thickness of t = 1 mm with a rectangular shape of 400 mm x 400 mm is used. The indentation depth is set to ID = 10 mm beneath the bed surface, the bed width is set to BW = 100 mm and the feed width is set to FW = 10 mm.

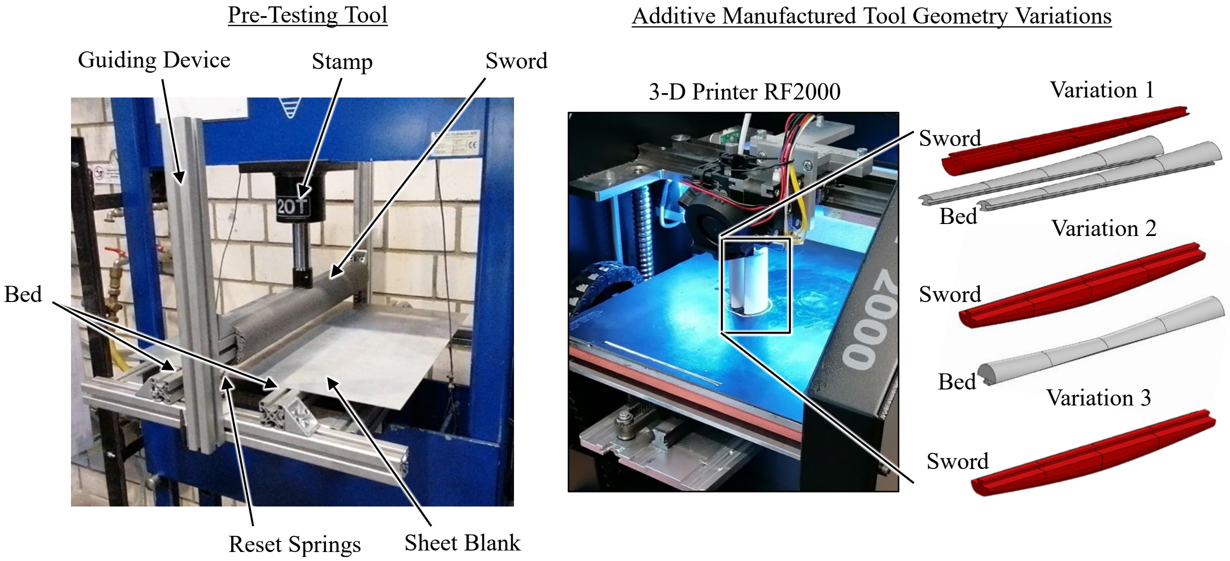

Fig. 4: Pre - testing tool (left), additive manufacturing of tools for spherical forming (right)

Three concept variations of sword and bed geometries are investigated (see Fig. 4 right). In variation 1, supports tapering transversely to the feed direction are provided as a bed and a matching laterally tapering centerboard is provided as a sword. The curved shape perpendicular to the feed direction is intended to generate a spherical bend in addition to the cylindrical bend in feed direction. In variation 2, a sword with a cambered shape and a one-sided support, which is the opposite shape to the cambered sword is used. The cambered form of the sword is intended to additionally press the sheet into a spherical shape. The shape of the bed is intended to provide a forming constraint on the underside of the sheet in the spherical direction. In variation 3, only a cambered sword is investigated for pressing a bend perpendicular to the feed direction. This variation thus provide the lowest forming constraint in the forming zone.

Variation 1. The forming behavior of sheets using the tool geometry of variation 1 is shown in Fig. 5. It can be seen that with the laterally curved sword and bed, bending occurs both in the feed direction and perpendicular to the feed direction. Thus, the desired spherical shape can be generated with variation 1.

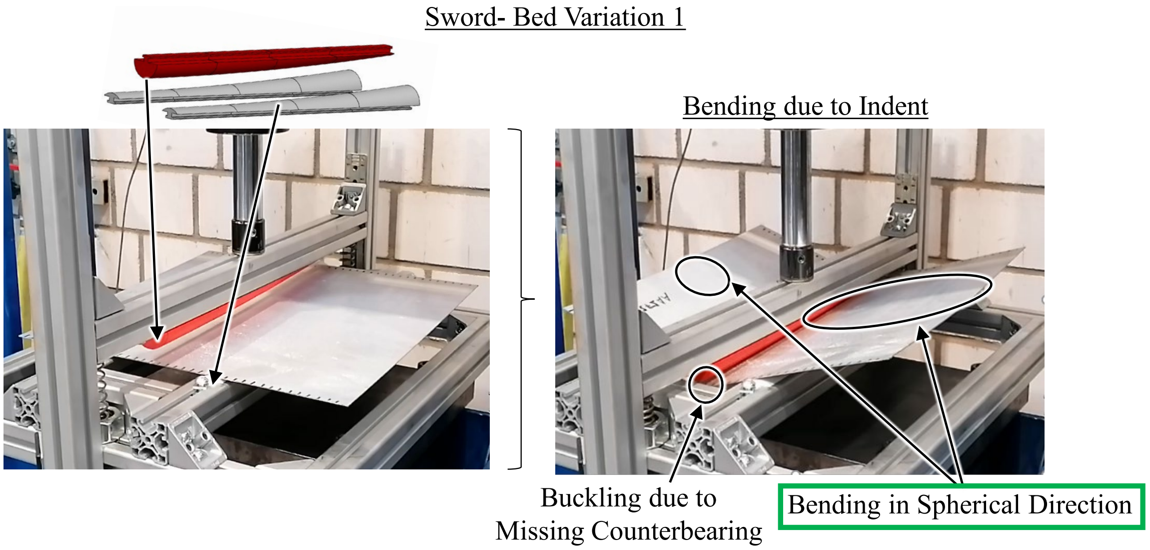

Fig. 5: Concept with curved bed and sword geometries (variation 1) for spherical forming

It is noticeable that the sheet under the sword buckles downwards on one side (see Fig. 5), since it does not recieve any counterpressure in this area. The form constraint coming from the bending geometry of the sword is thus reduced, which causes problems in dimensional accuracy. Nevertheless, this concept turns out to be very promising and can possibly be further optimized using elastic counter bearings under the sheet.

Variation 2. The forming behavior of sheets using the tool geometry of variation 2 is shown in Fig. 6. At the beginning of the forming process, a bending contrary to the targeted spherical direction appears in the middle of the plate. The cambered sword first comes into contact with the plate with its elevation in the center. When the sword is pressed further into the sheet, it stiffens over the length perpendicular to the feed direction. The sheet cannot change shape in the spherical direction. However, when the sheet is pushed further, it is observed that the initial stiffened area does not move along the length of the plate and remains at the edge of it (see Fig. 6 right). In the center of the plate, a spherical area with a curvature in and perpendicular to the feed direction is created. This is probably promoted by the concave bed. However, it can also be seen that an area is created in front of the feed area of the blank, in which the blank is strongly buckling. The concept of variation 2 is therefore not as suitable for spherical forming as variation 1.

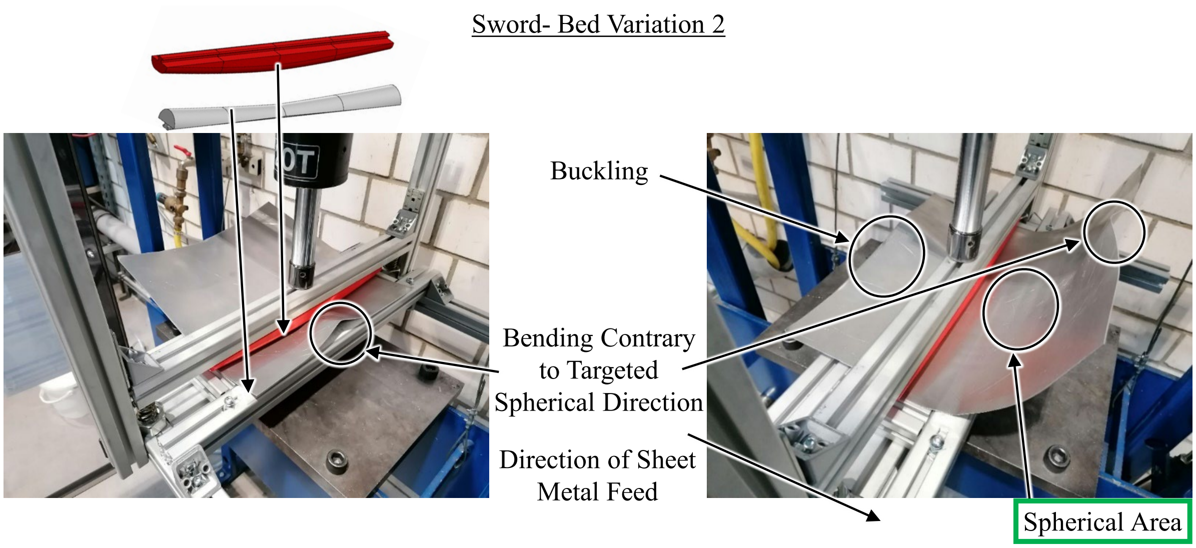

Fig. 6: Concept with cambered sword and concave bed geometry (variation 2) for spherical forming

Variation 3. The forming behavior of sheets using the tool geometry of variation 3 is shown in Fig. 7. It can be seen that comparable to variation 2 with the cambered sword, a bending occurs in the opposite direction to the targeted spherical geometry. In contrast to variation 2, the area bent against the spherical direction moves along with the sheet feed and does not remain stationary. A spherically shaped area can therefore not be generated only with a cambered sword without a corresponding bed. Variation 3 is therefore not suitable for spherical forming.

The different bending of the sheets caused by variant tool shapes can be explained by the occurrence of different stress states. During bending, compressive stresses prevail on the inside of the blade, where the sheets are compressed and tensile stresses on the other side where the sheets are widened [13].

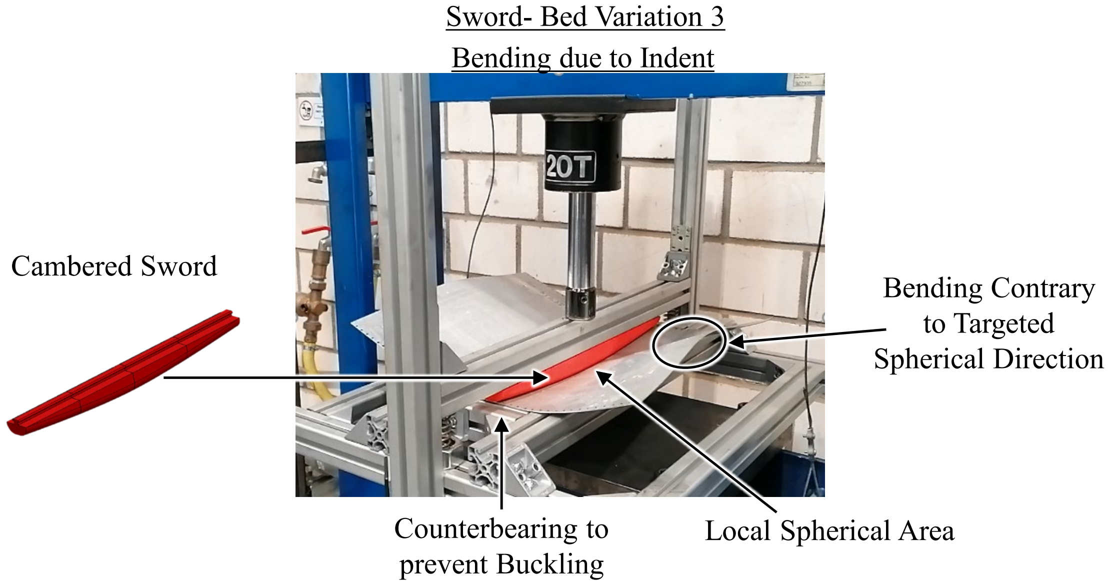

Fig. 7: Concept with cambered sword geometry (variation 3) for spherical forming

If the sheets are bent in the feed direction and perpendicular to it, compressive stresses occur with a positive superposition and maximum stress peaks in the area where bulging occurs (see Fig. 8).

In Variation 1, the opposing shape of the blade and bed probably results in lower maximum compressive stresses compared to Variation 2 where the maximum compressive stresses are positively amplified. The addition of the compressive stresses on the upper side of the sheet could initiate a bending in the opposite direction when the sheet is no longer under forming constraint. For Variation 3, the local stress state might differ compared to Variation 2 due to the symmetrical two-parted bed. The lower shape constraint leads to lower maximum compressive stresses and thus to lower stiffening bulging.

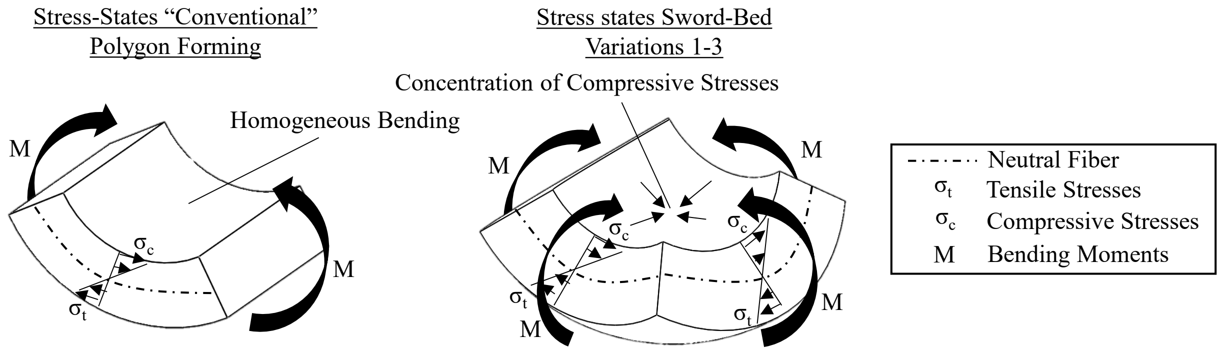

Fig. 8: Stress-states for cylindrical and spherical Polygon Forming

Summary and Outlook

In this research, an experimental tool for investigation of the polygon forming was developed. Cylindrical components were produced successfully from an aluminum alloy EN AW2024 - T351 commonly used in aircraft construction. In addition, different tool geometries for incremental spherical forming were investigated with a pre-testing tool. It could been shown that a curved sword with an associated bed on both sides leads to the most promising results regarding spherical forming. An elastic counter-bearing in the bed area could further improve the forming constraint and thus the dimensional accuracy of the spherical blanks.

In following works, a simulation will be carried out with which the polygon forming on the IFUM demonstrator can be mapped. In addition, the tool geometry according to variation 1 will be used in a numerical simulation for the forming of higher-strength AA2024, with increased sheet thickness of $t = 3.2$ mm. Therefore, iterative optimizations are made to compensate material springback and avoid buckling. After an iterative numerical optimization of the geometry, tool components will be manufactured with which spherical forming could be performed on the scaled polygon forming IFUM demonstrator.

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