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Reverse rigid body motion in multi-stage single point incremental forming

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Abstract. This paper provides an analysis of the Rigid Body Motion (RBM) in multi-stage Single Point Incremental Forming of a cylindrical cup. The RBM is studied using Digital Image Correlation to track the material in each contour of the tool, resulting in a better understanding of the RBM phenomenon than has been shown in literature. The study shows that the highest Z-translations of the midpoint of the cone take place in the last contours of each stage, where these RBM peaks also increase per stage. An interesting observation is a reverse rigid body motion, appearing in the contours close to the end of a stage, right before the sudden drop of the bottom in the last contours. This causes flattening of the bottom of the cone and results in a smaller RBM per stage for the later forming stages. Additionally, the stepover between two intermediate stages has been shown to have an important effect on the stepped features appearing in the bottom, but did not have a significant effect on the accuracy of the midpoint of the cone.

Introduction

As a flexible sheet metal forming technique, Single Point Incremental Forming (SPIF) shows great potential as an alternative for producing small batch sizes and customized parts due to the elimination of expensive dies. Additionally, the small plastically deformed zone located in the direct vicinity of the contact area between the tool and workpiece results in much higher strains and therefore an increased formability compared to conventional processes like deep drawing [1]. However, two important challenges remain: the low geometric accuracy due to unwanted deformations and the forming limits, that result in failure of the part at certain wall angles. As a method of increasing the forming limits of parts produced with SPIF, multi-stage forming can be considered [2], as well as dynamic local heating [3]. This paper will focus on the first strategy, which allows forming parts with much higher wall angles, but also introduces unwanted deformations such as Rigid Body Motion (RBM). In this study, the rigid body motion for forming a cylindrical cup in multiple stages will be analyzed. The comparison between different stages will be performed by analyzing the difference in depth of the bottom in between two contours, and will be addressed as the incremental RBM.

Rigid Body Motion (RBM) in Multi-stage SPIF

In the previous paragraph, multi-stage incremental forming has been proposed as one of the possibilities for overcoming the forming limits and preventing the part from failure. Despite its success in increasing the process limits, multi-stage forming also induces extra unwanted deformations, which already showed as stepped features in the bottom of the produced cone when multi-stage forming was described by Duflou et al. [2]. These features are induced by forming the part in multiple stages, when additional unwanted deformations occur due to the geometrical stiffness of the preform in each stage, and take place in the forming direction.

The first attempts on multi-stage forming of a cylinder to increase the maximum achievable wall angle limits did not take the unwanted stepped features into account when designing the multi-stage strategy and intermediate shapes, resulting in large geometrical deviations [2]. Later, Malhotra et al. [5] firstly used the term Rigid Body Motion (RBM) to describe these unwanted stepped features induced by the multi-stage approach and described analytical formulas to calculate the rigid body translation for out-to-in (OI) and in-to-out (IO) toolpath strategies. OI toolpaths, where the tool starts close to the backing plate and increases in depth, are commonly used in multistage strategies. IO toolpaths on the other hand, start inside the shape and gradually move outwards, which results in a different displacement of the material and different deformations. Based on their predicted RBM Malhotra et al. proposed a new strategy that combines an OI and IO toolpath within one stage, in order to compensate for the predicted rigid body translations. With this strategy, they were able to form a 90 degree wall angle cylindrical cup with a near flat base. Xu et al. [6] updated these RBM predictions by relating the material constants to the blank properties. Lingam et al. [7] analyzed the existing prediction models of Malhotra et al. [5] and Xu et al. [6] and included force predictions in their model to take the elastic deflections of the tool and sheet during forming into account. Later, Lingam et al. [8] proposed a methodology that combines IO and OI stages based on the strains, where the best forming sequence of features can be selected and unwanted RBM features are avoided by predicting the rigid body translation. Ndip-Agbor et al. [9] on the other hand also studied RBM and came to the conclusion that previous studies showed little insight in why RBM occurs and tended to focus mostly on specific cases or empirical observations. To compensate for this literature gap, they related the RBM to the 3D contact region between tool and sheet and used this as the basis for their RBM predictions. Wu et al. [10] proposed a new methodology based on both OI and IO toolpaths together with design rules for constructing intermediate stages for a vase shape with the aim of improving thickness distributions and reducing RBM. Later, Wu et al. [11] extended their strategy for maximal thickness distributions and minimal RBM to a truncated pyramid. Gupta et al. [12] did manage to eliminate the RBM for a more complex aerospace component, but needed multiple trials before succeeding.

Despite significant reported research efforts on this topic, no in-depth empirical studies on the rigid body translations per individual tool contour (one pass of the tool at a constant depth) have been performed. This study aims to investigate the RBM in each stage of forming, by measuring the Z-translation between tool contours of the different stages using Digital Image Correlation (DIC). This will result in a broader understanding of the RBM phenomenon in multi-stage incremental forming.

Materials and methods

The studied workpiece shape is a cylindrical cup with a diameter of 142 mm and a depth of 35 mm, on which two strategies of multi-stage forming are applied. The first forming strategy (Fig. 1.a) was described by Duflou et al. [2], where intermediate conical shapes with increasing wall angles in steps of 10 degrees are formed (Fig. 1.a). The maximum stepover between two subsequent stages is not constant and is the largest between stage 1 and 2 with a distance of 9.16 mm (perpendicular to the tool). In a second strategy (Fig. 1.b), a smaller maximum stepover of 2.5 mm is considered and kept constant for all stages. This results in 13 shapes, starting from a cone with a 50 degrees wall angle up to the desired cylindrical cup of 90 degrees. The multi-stage experiments are conducted with a hemispherical tool of 10 mm diameter on a KUKA KR500MT robotic arm with a feedrate of 2000 mm/min on 1.5 mm sheets of Aluminum alloy 5754 (AlMg3). The sheet is clamped with a circumferential backing plate of 184 mm diameter and Nuto 46 lubrication oil is applied before forming. A contouring toolpath forms the part with a scallop width of 1 mm. This corresponds to a stepdown in the Z-direction of $sw * \sin(\alpha)$ with sw the scallop

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width of 1 mm and α the wall angle. For the first shape of both strategies, a cone of 50 degrees, the stepdown corresponds to 0.766 mm.

The same DIC setup (Fig. 1.c) is used as in [13] with two Mako G-507B Allied Vision cameras and Edmund Optics lenses with a focal length of 35 mm. The DC-LEDS together with a concave shield ensure diffuse lighting conditions. With the bottom half of the part as the field of view, the setup exploits the symmetrical properties of the part to make sure all areas in the region of interest (ROI) are visible by both cameras at all times during forming. The speckles are applied by screen printing. The DIC images are taken when the tool is outside the field of view, to eliminate capturing the high local elastic deformations around the tool tip. Additional images are taken before forming, in order to eliminate noise, and an extra image is taken after finishing a shape and retracting the tool. The software used for calculating the correlations is MatchID [14] with an update of the reference image in each time step, in order to cope with the high deformations induced by the process. After correlating the images in the time and space domain with the parameters indicated in Table 1, the coordinate system of each image is transformed to the local coordinate system of the workpiece-robot setup as presented in Fig. 1.c.

Table 1: Correlation parameters.

Correlation software	**MatchID**
Subset size [pixels]	39x39
Step size [pixels]	10
Correlation algorithm	Zero-Normalised Sum of Squared Differences (ZNSSD)
Interpolation	Bicubic Spline Interpolation
Shape function	Quadratic
Stereo transformation	Quadratic

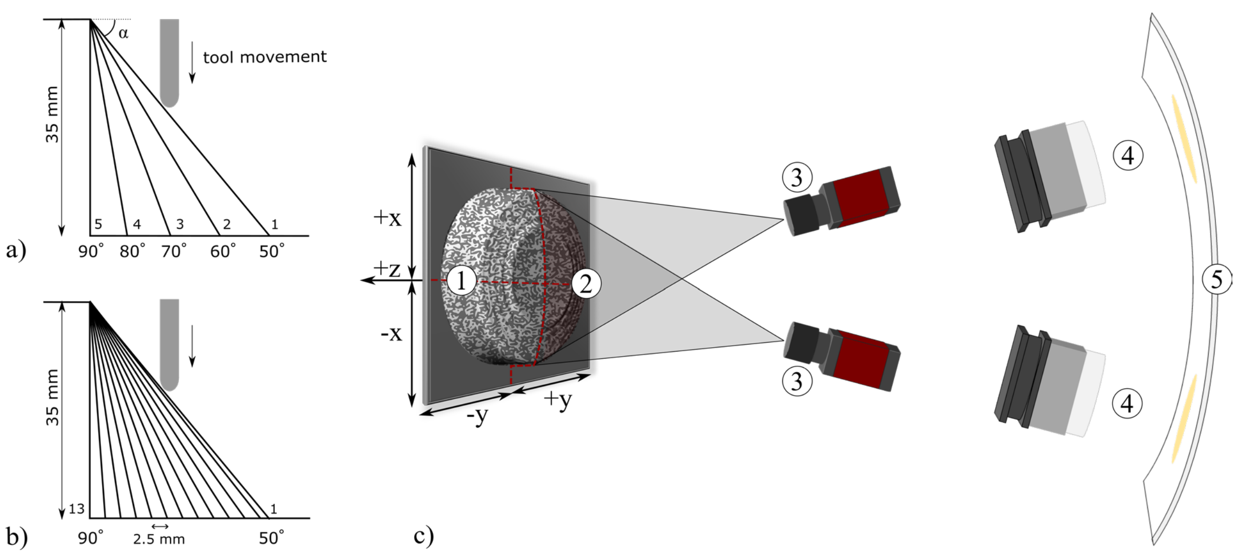

Fig. 1: a) Strategy 1, b) strategy 2 and c) DIC setup with (1) a clamped part, (2) the field of view, (3) the cameras, (4) the spotlights and (5) a concave shield to diffuse the light. The origin of the coordinate system is located in the middle of the (originally flat) sheet, with the X- and Y-axes as indicated in the figure and the Z-axis pointing opposite to the sheet forming direction.

Results and Discussion

The DIC results are compared by calculating the incremental rigid body deformation of the midpoint of the cone (located in the unformed bottom) between two subsequent contours of the tool. A contour is defined as one pass of the tool at a constant depth level. Each of these contouring tool passes can induce an unwanted rigid body deformation of the bottom of the cone due to the geometrical stiffness of a preformed part. The RBM per contour is defined as the difference in Z-coordinates between the current contour and the previous one and is visible in Fig. 2.a for the first strategy and in Fig. 2.c for the second. As can be seen, when forming the first stage starting from a flat sheet, the rigid body motion is first upwards (A) due to the bulging of the bottom in the first contours. Then, the RBM shows an overshoot downwards (B), which is larger than the stepdown in the Z-direction.

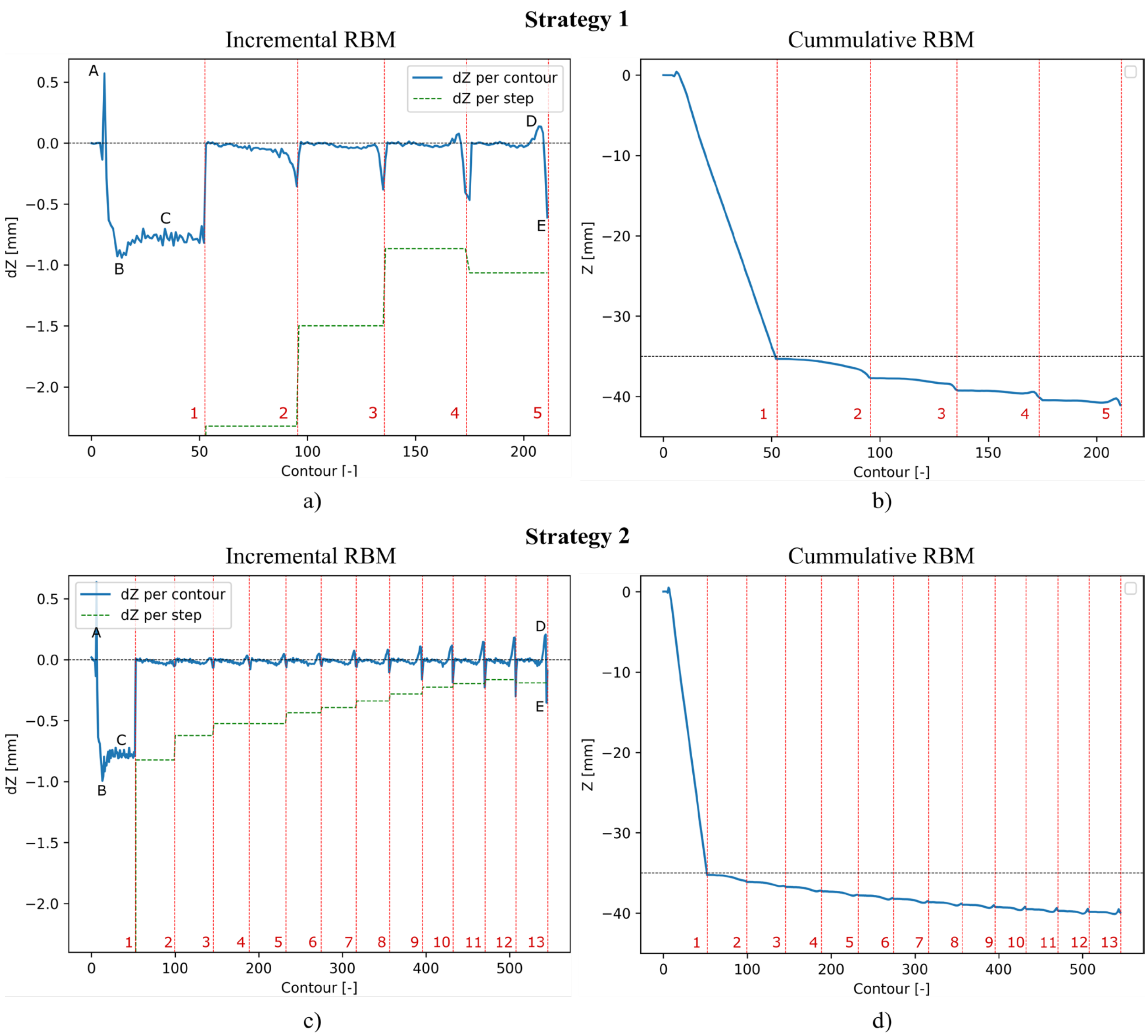

Fig. 2. Incremental and cummulative translations of the midpoint of the workpiece, respectively left and right. (a, c) Strategy 1 and 2, respectively: incremental Z-translation per contour (full line) for the midpoint of the cone and its overal Z-translation per stage (dashed line). (b, d) Strategy 1 and 2, respectively: Z coordinates of the midpoint per contour, with the horizontal line indicating the desired cone depth.

The incremental RBM in the first stage is targeted to be equal to the stepdown of 0.766 mm in each contour of the first stage and zero in the next stages, to keep the bottom flat. After the initial overshoot of the absolute incremental RBM (B), the RBM stays approximately constant for the remaining contours in the first stage and corresponds to the stepdown (C). In the second and subsequent stages, the RBM is desired to stay zero, in order to avoid further unwanted deformations. However, the stepped unwanted features are mostly formed in the last contours of the toolpath for each stage of forming, where the RBM suddenly increases in absolute value (E). Right before this RBM peak takes place, a reverse rigid body translation can be observed (D) in the later stages. Due to this reverse RBM, the bottom of the cone moves upwards and slightly decreases the unwanted deformation by flattening the bottom. Additionally, both the reverse RBM and RBM peak in the last contours get higher in absolute value in each multi-stage step. The fact that the RBM is reversed and slightly flattens the bottom again, has not been shown in literature yet and provides a necessary insight in the mechanics of the RBM.

The total RBM per stage is also visible in Fig. 2.a and 2.c (dashed line) and decreases in absolute value in each stage, except for the last stage, where a slight increase is visible. The highest rigid body translations therefore take place in the first stages of the multi-stage approach. As can be seen, both the incremental RBM (full line) and total RBM per stage (dashed line) of the second strategy are much lower in absolute value than the first strategy. This is due to the smaller stepover between two intermediate stages, which lowers the material movement and therefore the rigid body translation of the midpoint of the cone per contour.

The Z-translation of the midpoint of the cone is visible in Fig. 2.b and 2.d for the first and second strategy respectively. Here, the reverse RBM and the RBM peak from the previous images are also visible. When inspecting the Z-translation of the midpoint of the cone, the final Z-position, and therefore total RBM of the multi-stage cone after forming, is for both strategies almost equal (-41 mm for Strategy 1 and -40 mm for Strategy 2). This shows that with smaller stepovers between subsequent stages, the (incremental) RBM per stage is smaller, but this does not have a significant effect on reducing the total (cumulative) RBM after forming.

Although the total RBM of the midpoint of the cone after forming is almost equal for both strategies, Fig. 3 shows that the stepped features are less outspoken for the second strategy, thanks to the smaller stepover between two subsequent stages. The most outspoken stepped feature is located between the first and second stage of the first strategy, where the maximum stepover is the highest. This figure also shows the material trajectory for the two strategies. As can be seen, the material moves a little more upward in the second strategy. This strategy is characterized by a more horizontal material movement, which, in combination with the smaller stepover, leads to higher radial forces, resulting in an upwards lift of the bottom of the cone.

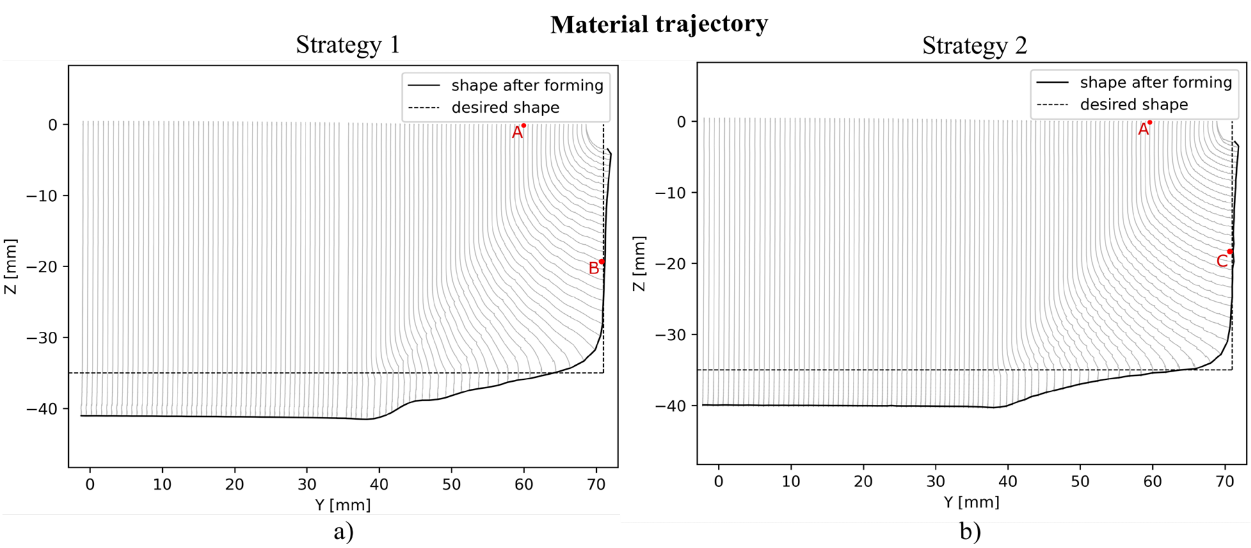

Fig. 3. Material trajectory and final shape after forming compared to the desired cylindrical shape for the first (a) and second (b) strategy.

Fig. 4 shows the difference between the reverse rigid body translation (D in Fig. 2.a) and the regular RBM peak in the last contours of a stage (E in Fig. 2.a). As can be seen, the material movement around the tool is directed axially (in the negative Z-direction) in Fig. 4.b, resulting in a downwards movement of the bottom of the cone. On the other hand, for the reverse RBM in Fig. 4.a, the material movement around the tool is directed more towards the walls (in the Y-direction). This results in a higher radial force and therefore a movement of the bottom in the positive Z-direction, due to the geometrical stiffness of the preformed features. An additional observation in this figure is the fact that the RBM and reverse RBM are not depending on the wall angles of the shape and are constant over the section, except close to the tool-workpiece contact zone.

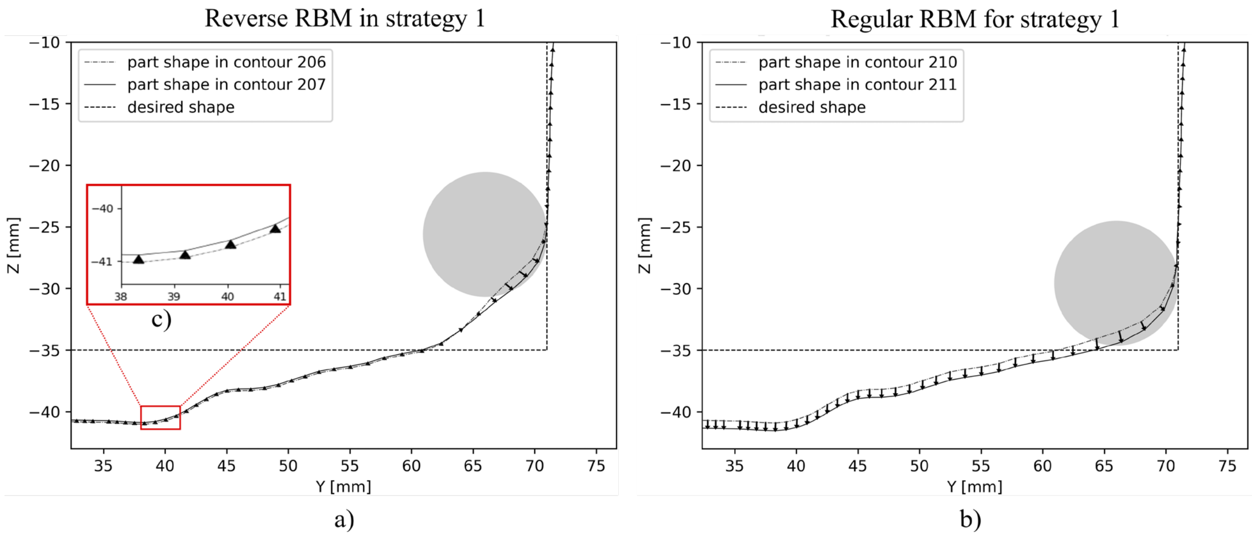

Fig. 4. (a) Material trajectory and reverse RBM between contours 206 and 207 of the tool (zone D) for the first strategy. (b) Material trajectory and peak RBM in the last contours 210-211 of the tool (zone E). (c) Close-up of the reverse RBM.

Conclusion and outlook

In this paper, an empirical study based on DIC measurements is carried out to analyze the rigid body translation per tool contour during multi-stage forming. A first observation is the bulging effect in the first contours of the first stage, which is a single-stage approach. Here, the midpoint of the cone first starts moving upwards due to the bulging effect in the first contours of the toolpath. After a few contours, a large overshoot of the RBM in the negative direction takes place right before an equilibrium equal to the stepdown is reached.

A second observation is visible in the next stages: after a few stages in the multi-stage approach, a reverse rigid body motion is visible in the later contours, followed by a sudden drop of the bottom of the cone. These effects can be explained by analyzing the tool-workpiece contact zone and material trajectory per contour: the RBM is induced by a downwards movement of the material in combination with a high geometrical stiffness of the already formed part. The reverse RBM on the other hand, appears when the material at the tool tip is mostly undergoing radial outward directed loading. Due to a high geometrical stiffness, this radial force induces an upwards movement of the already formed bottom part. Both the RBM and the reverse RBM peaks increase in each stage of the multi-stage forming, which is due to the shape of the intermediate stages and the tool-workpiece contact zone.

A third observation is the decrease in total absolute RBM per stage, except for the last stage, where the stage RBM slightly increases again. This decrease in total absolute RBM per stage might seem contradictory, since the absolute incremental RBM in the last contours of the tool increases in each stage. However, the increase in reverse RBM in each stage partly counteracts the effect of the RBM increase, which explains the decrease in total RBM per stage.

A last observation shows that the incremental RBM per contour and per stage is lower for strategy 2 with smaller stepovers between two intermediate stages. This can be explained by the material movement between two contours, which is smaller for smaller stepovers and therefore results in smaller rigid body translations. However, this does not have a significant effect on the total accuracy of the midpoint of the cone, since strategy 2 also consists of additional intermediate stages. Even though no significant difference in RBM of the midpoint of the cone can be observed, the smaller stepover did result in less outspoken stepped features in the bottom.

This study shows that the RBM indeed appears to be linked to the tool-workpiece contact zone, as was assumed in literature, and also reveals a reverse rigid body translation appearing in the later stages of a multi-stage approach. Possible future work entails a study on the relationship between the incremental RBM and the tool-workpiece contact zone, while also taking into account the geometrical stiffness of the part due to previous forming stages. Another aspect for future work includes a study of the geometric ratio to increase the robustness for knowledge generalization.

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