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A Mixed Double-Sided Incremental Forming Toolpath Strategy for Improved Geometric Accuracy

Double-sided incremental forming (DSIF) is a relatively new dieless forming process which uses two hemispherical ended tools, one on each side of the sheet, moving along a predefined trajectory to locally deform a peripherally clamped sheet of metal. DSIF provides greater process flexibility, higher formability, and eliminates the tooling cost when compared to conventional sheet forming processes. While DSIF provides much improved geometric accuracy compared to other incremental forming processes, current toolpath planning strategies suffer from long forming times. A novel mixed double-sided incremental forming (MDSIF) toolpath strategy is proposed in the present study. It simultaneously reduces the total forming time by half while preserving the best currently achievable geometric accuracy. The effect of the forming parameters, i.e., of the incremental depth and of tool positioning on the geometric accuracy of the parts formed with MDSIF was investigated and compared to those formed by traditional DSIF strategies.
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Keywords: incremental forming, geometric accuracy, toolpath strategy

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1 Introduction

Incremental forming is a relatively new die-less forming process with several desirable characteristics when utilized for small batch production and prototyping of sheet metal parts. In incremental forming, a sheet of metal is securely clamped peripherally and is locally deformed by one or more simple hemispherical ended tools moving along a trajectory predefined by the part geometry. The accumulation of the local deformations gives the sheet its final shape. Unlike conventional sheet metal forming processes such as stamping that need expensive dies and punches that are specific to the part shape being formed, incremental forming uses part-shape-independent tools while maintaining a relatively low energy demand [1,2]. With the increasing demand for customization in manufacturing, this inherent flexibility and negligible tooling cost make incremental forming ideal for customization in sheet forming [3,4]. Additionally, it has also been shown that incremental forming results in substantially increased formability as compared to conventional sheet metal forming [5–7].

Single point incremental forming (SPIF) is the simplest form of incremental forming in that the process only utilizes one tool to locally deform the material (Fig. 1(*a*)). This local stretching deformation mechanics provides a different and higher forming limit curve from the traditional one [8,9], and it is found that the formability increases with the decrease of the incremental depth [10]. However, the geometric accuracy of SPIF is poor due to the undesirable bending that occurs in the region between the forming tool and the fixture [11]. Some attempts have been made to alleviate this issue. Ambrogio et al. [12] attempted to optimize the parameters of SPIF to compensate for the springback. Lu et al. [13] proposed a feature-based toolpath generation in order to achieve accurate local features. Allwood et al. [14] tried the use of partially cut-out blanks to eliminate the deformation in the undesired regions, but concluded that a backing plate is necessary for improvement of the geometric accuracy in SPIF. Multipass SPIF approaches have also been attempted in an effort to increase the achievable formability in SPIF while also attaining improved geometric accuracy [15–18]. However, these efforts still cannot overcome the aforementioned global bending effect which requires that parts in single pass or multipass SPIF be formed close to the edge of the forming area opening if any reasonable geometric accuracy is to be achieved. Fiorentino et al. [19], Attanasio et al. [20], and Tekkaya et al. [21] utilized supporting dies beneath the sheet during SPIF to control the inherently poor geometric accuracy in a variant of incremental forming known as two-point incremental forming. This method can be extended toward an array of flexible support features, which ultimately leads to a die made of pins that may require an interpolation polymer-layer to smooth out the transitions between pin tips [22]. Hybrid processes which combine incremental forming with stretching forming [23] and with multipoint forming [24] that lead to uniform thickness distribution have been investigated. However, these approaches require some form of a bottom die, which compromises process flexibility that is a key desirable characteristic of incremental forming.

Another variant of incremental forming is DSIF adds another tool on the opposing side of the sheet that acts as a moving support tool [25–27], as shown in Fig. 1(*b*). This supporting tool is programed to move along with the forming tool acting as a local die to support or squeeze the sheet, while retaining the shape-independent-tooling nature of incremental forming. Previous work by the authors in Ref. [28] investigated a conventional DSIF toolpath (Fig. 1(*b*)) and found that while the geometric accuracy was improved as compared to SPIF there was a loss of contact between the supporting tool and the sheet during the forming process. This resulted in the process degenerating into SPIF and significant geometric deviation in the formed part [28]. One approach to solving this issue was proposed by Meier et al. [29,30] who developed a combined force–displacement control strategy for the bottom tool to go beyond the sine law, which was used in conventional DSIF toolpaths, to position the supporting tool and prevent loss of contact of the supporting tool. However, this technique depends on the accuracy of thickness prediction, which has not been fully developed for an arbitrary freeform geometry. Furthermore, for unique material manipulation, it is often advantageous to run both tools in displacement control.

As an alternative, a novel toolpath strategy called accumulative double-sided incremental forming (ADSIF) was developed by Malhotra et al. [31] through changing the nature of the toolpath used in DSIF. In conventional DSIF (Fig. 1(*b*)), the tools move in the negative *Z*-direction by an incremental depth ΔZ, and deform the sheet along a shape-dependent *XY*-trajectory at that depth, then the tools move down by another ΔZ, and repeat the process until the tools reach the final depth of the desired geometry. The tools, consequently, move from the outside of the desired geometry to the inside while traveling vertically from the top to the bottom of the component to be formed. However, in ADSIF the tools move from the inside of the desired part outward without moving down in the depth direction (Fig. 1(*c*)). The toolpath in ADSIF is designed such that the tools form a shape-dependent loop of the material to the specified incremental depth ΔZ, then the tools travel outward without moving down and form another loop of the undeformed material to the subsequent ΔZ, thus causing the previously formed shape to be displaced by rigid body motion in the direction normal to the in-plane motion of the tools. In the end, the depth of the final part is achieved via accumulated rigid body motion of the already formed part of the metal sheet in each incremental deformation. There is no loss of contact between the sheet and the tools during the forming. Because the tools are kept within a given horizontal plane and moving outward, the thickness does not have to be predicted a priori to position the tools, thus resolving the aforementioned issue with the conventional DSIF toolpath strategy. Along with an improvement in geometric accuracy of the formed part [32] (Fig. 2), ADSIF also enables greater formability [31] and better fatigue performance [33]. However, as shown in Fig. 2, the use of greater incremental depth (ΔZ, in Fig. 1(*c*)) causes a reduction in part accuracy. In summary, ADSIF requires the use of a very small incremental depth in order to form an accurate geometry which results in significantly increased forming time [31].

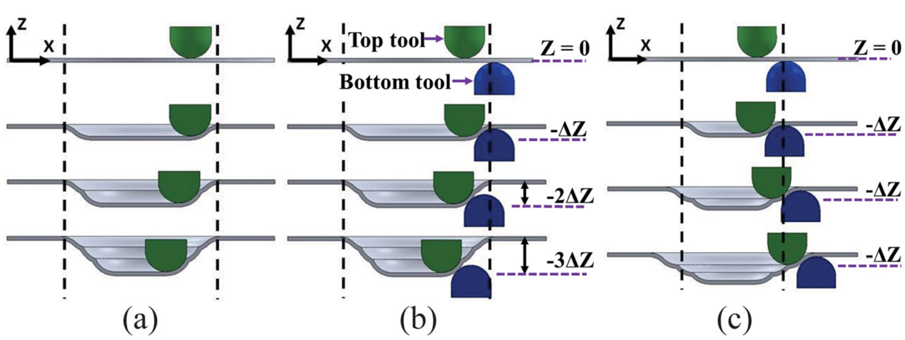

Fig. 1 Toolpath strategies in incremental forming: (*a*) SPIF, (*b*) DSIF, and (*c*) ADSIF

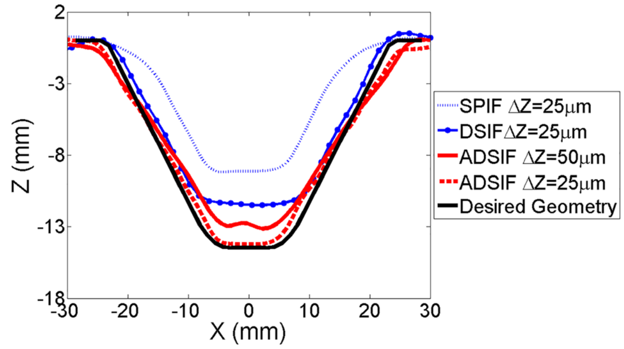

Fig. 2 Improved geometric accuracy for a 40 deg cone with ADSIF and the influence of incremental depth in ADSIF on geometric accuracy (data obtained from Ref. [31])

This paper proposes a MDSIF toolpath strategy to reduce the aforementioned forming time while achieving high geometric accuracy of the formed part. In MDSIF, the sheet metal is first formed with ADSIF and then reformed with DSIF without being taken out from the clamping device. The geometric accuracy of the parts formed with DSIF, ADSIF, and MDSIF are evaluated experimentally in terms of the effects of incremental depth and tool positioning used. Also, the thickness profiles of these parts are acquired using a nondestructive optical detection method. The conclusions drawn from the above experiments are discussed in terms of their implications on toolpath planning. Possibilities for future work are also discussed.

2 Experimental Methodology

2.1 MDSIF Toolpath Strategy. In the MDSIF strategy, a part is first preformed using ADSIF with a relatively large incremental depth to ensure that the loss of contact between the supporting tool and the sheet is avoided and to reduce the forming time. This ADSIF processing step acts as a rough forming pass to obtain the formed geometry close to the desired geometry. Then, without unclamping the fixture or moving the metal sheet, DSIF is used as the second forming step on the preformed part to fine tune the geometric accuracy of the part.

As mentioned before, ADSIF is able to provide part closer to the as-designed geometry than DSIF in the first step, where the global bending problem is hard to eliminate in DSIF process without using a backing plate [4]. The forming force in the second forming step will hence be reduced due to smaller plastic deformation. Therefore, global bending and loss of contact between the tools and the sheet due to compliance will be reduced, and the geometric accuracy will be improved.

In the most general sense, DSIF can refer to any strategy utilizing two stylus-like tools to locally deform a metal sheet, as previously described. However, in this study, DSIF is used to specifically refer to conventional tool paths in which the two tools progress inward and downward to form the desired part (Fig. 1(*b*)). This is in contrast to ADSIF (Fig. 1(*c*)). MDSIF consists of using the two stages of forming. For convenience, the terms A-stage and D-stage will be used to represent the ADSIF or DSIF stages in MDSIF, respectively.

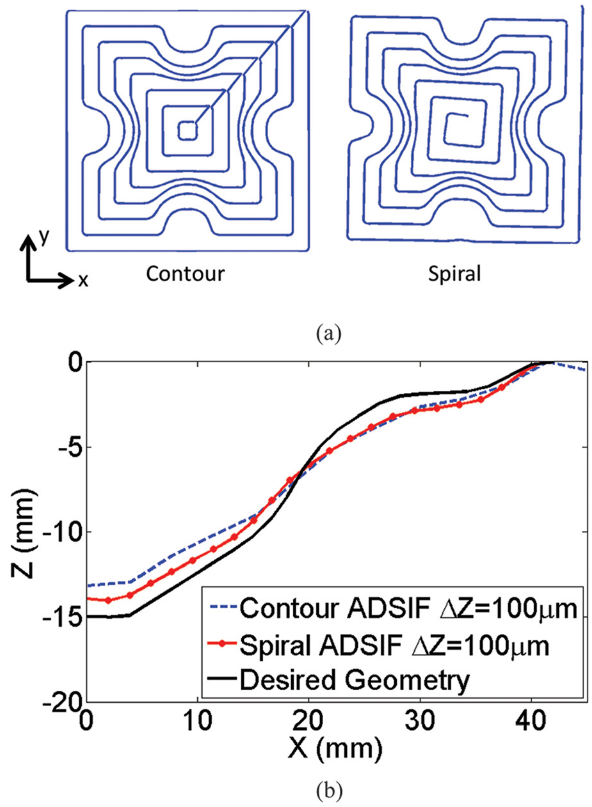

Fig. 4 Comparison between a contour and a spiral toolpath in ADSIF: (*a*) toolpath and (*b*) geometric accuracy

2.2 Experimental Setup. To experimentally examine the MDSIF strategy, a pyramidal part (Fig. 3) with a concave pocket on each face was experimentally formed. The cross section of the desired geometry is given in Fig. 4. Note that this geometry cannot be generated by SPIF due to the convex–concave nature of the part. The sheet material used was 0.5-mm-thick aluminum alloy AA2024-T3 which is a lightweight material that is used in aerospace applications for its high strength to weight ratio, high toughness, and good resistance to stress corrosion effects [34]. The mechanical properties of the experimental material are given in Table 1. Both tools were 5 mm diameter hemispherical ended tools made of A2 tool steel. The tool speed in the experiment was fixed at 5 mm/s. The experiments were performed on a custom-built DSIF machine system (Fig. 5) with a forming area of 250 mm × 250 mm and capable of forming parts up to 100 mm in depth on either side of the sheet. The machine has a positioning accuracy to within 30 μm. No backing plate was used in the experiment which allows for the incremental forming application

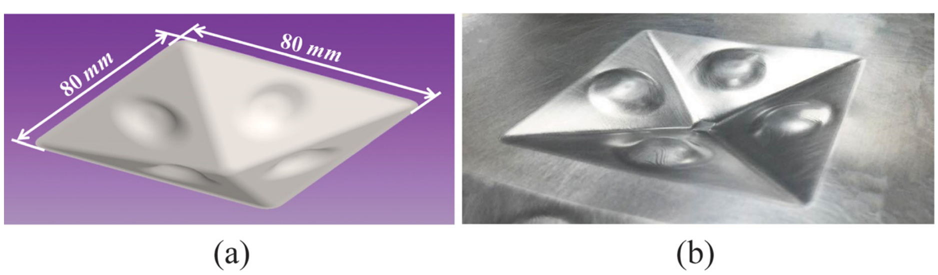

Fig. 3 (*a*) CAD model of desired geometry and (*b*) formed part

Table 1 Material mechanical properties of AA2024-T3

Density (kg/m^3)	Young's modulus (GPa)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)
2796	73	283	447	14

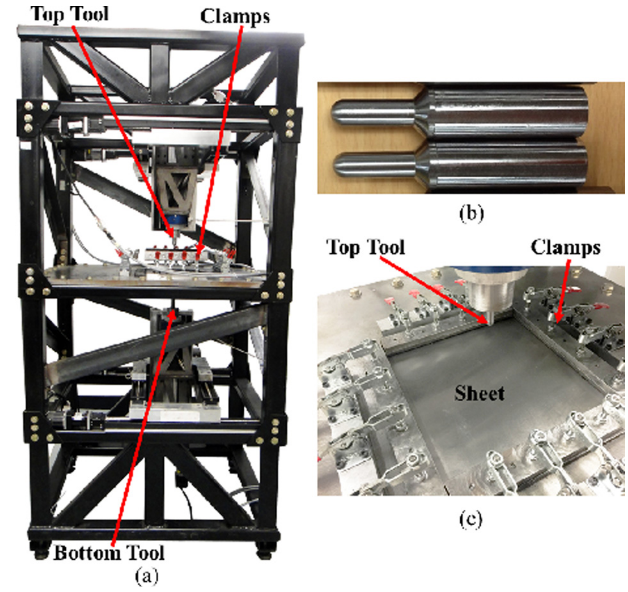

Fig. 5 DSIF machine system: (*a*) DSIF machine, (*b*) forming tools, and (*c*) clamping system

of generic part sizes and does not limit the desired flexibility of the process.

2.3 Toolpath Parameters. The geometric accuracy of the formed parts was explored as a function of two key toolpath parameters, namely, the incremental depth and the relative position of the supporting tool. In DSIF, the squeeze factor s (Fig. 6(*a*)) indicates the magnitude of squeezing within the local area between the tools, while the surface normal is used to orient the tip of the supporting tool with respect to the forming tool, or top tool. When $s = 1.0$, the bottom tool is just touching the sheet and when $s < 1.0$, the top tool and the bottom tool are actively squeezing the sheet metal. Values of $s = 1.0$, 0.9, 0.8, 0.75 were used in DSIF and in the D-stage of MDSIF to study the effect of sheet squeezing on the achievable geometric accuracy. The position of the tools in ADSIF and A-stage was defined via two parameters D (distance between the axes of the two tools) and S (vertical distance between the bottom of the sheet and the tip of the bottom tool), which were fixed at 2.5 mm and 0.43 mm, respectively (Fig. 6(*b*)). The geometric accuracies of the parts formed by MDSIF were compared to that achievable with DSIF and ADSIF toolpaths using a low incremental depth of 25 μm and a high incremental depth of 100 μm. The D and S values for ADSIF were obtained from the previous work [35] since they yielded the best possible geometric accuracy. In MDSIF, the same incremental depth was used for both the A-stage and D-stage. Additionally, MDSIF was also performed using an incremental depth of 80 μm, 100 μm, and 120 μm. For all toolpaths, a spiral tool motion strategy was used since it has shown a better geometric accuracy as compared to contour toolpaths, which is illustrated by the comparison of cross section profiles of the inner surface (Fig. 4). The specifications of the experiments are summarized in Table 2, where b is the base time, to which every process is compared, and equals to 7 hrs under the previously set forming speed (5 mm/s).

2.4 Geometric Deviation Measurement. The inner surfaces of the formed parts were scanned using a Konica Minolta laser scanner. Then, commercial software was used to generate a surface fit of the point cloud. The inner surface was chosen since it is the surface based on which the forming toolpaths are generated. The profiles were then compared to the desired geometry. In this work, the geometric error was defined as the normal distance from each point on the desired geometry to the corresponding point on the formed part (Fig. 7). Figure 8 shows the 3D comparison between the desired part and the formed part.

In the current work, the root mean square (RMS) value of the errors along the cross section on a plane of symmetry ($Y = 0$ in Fig. 8) will be used as a criterion to compare the deviations of the key features of the formed parts, i.e., the depth and the pocket features formed by using different strategies

$$E = \sqrt{\frac{1}{n}(e_1^2 + e_2^2 + \ldots + e_n^2)} \qquad (1)$$

3 Experimental Results and Discussion

This section first discusses the influence of incremental depth and tool positioning on geometric accuracy in DSIF, ADSIF, and MDSIF toolpath strategies along with the observation of a special

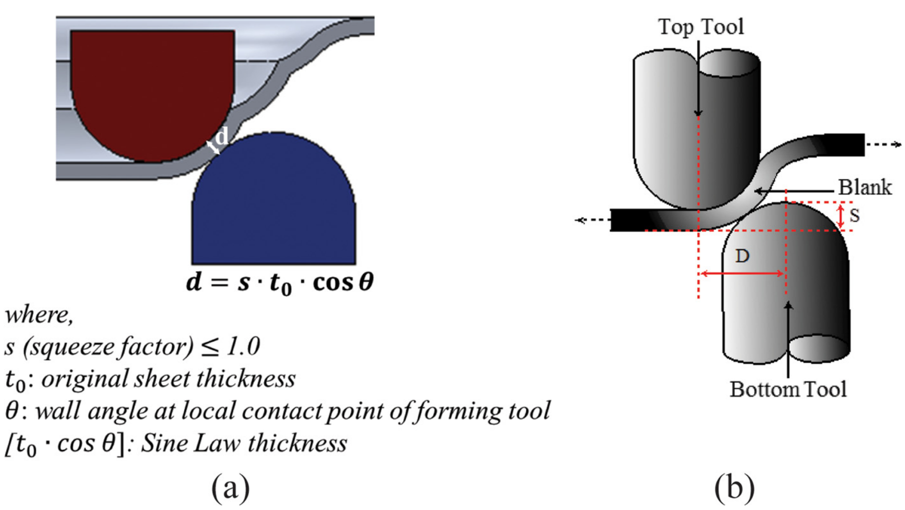

Fig. 6 Definition of tool positioning parameters: (*a*) squeeze factor *s* in DSIF and (*b*) *S* and *D* in ADSIF

Table 2 Specifications of the experiments

Process		Incremental depth, ΔZ (μm)		Forming time ($b = 7$ hrs)		Squeeze factor, s
ADSIF		25		b		N/A
		100		$0.25b$		
DSIF		25		b		1.00, 0.90, 0.80, 0.75
		100		$0.25b$		
MDSIF	A-Stage	80	80	$0.62b$	$0.31b$	N/A
	D-Stage		80		$0.31b$	1.00, 0.90, 0.80, 0.75
MDSIF	A-Stage	100	100	$0.50b$	$0.25b$	N/A
	D-Stage		100		$0.25b$	1.00, 0.90, 0.80, 0.75
MDSIF	A-Stage	120	120	$0.42b$	$0.21b$	N/A
	D-Stage		120		$0.21b$	1.00, 0.90, 0.80, 0.75

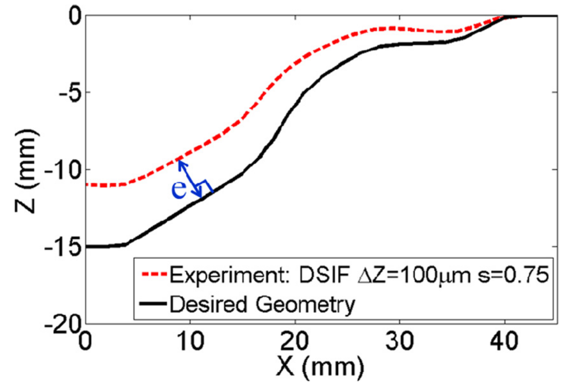

Fig. 7 Definition of geometric error used in this work

case in the MDSIF process. The thickness profiles in DSIF, ADSIF, and MDSIF are discussed in the second part.

3.1 Geometric Accuracy. The geometric deviations of different forming strategies in terms of the RMS error, as expressed by Eq. (1), are plotted in Fig. 9, grouped by different squeeze factors used in DSIF and D-stage. Note that in the ADSIF case, no squeeze factor was used, hence, the results of ADSIF are represented by two horizontal lines for two different incremental depths. In ADSIF, a reduction in incremental depth increases the part accuracy, as mentioned earlier in the Introduction. Utilizing ADSIF with incremental depth $\Delta Z = 25\,\mu$m, the same incremental depth that was used in our previous work to demonstrate the advantage of ADSIF [31], leads to a geometric accuracy of 0.49 mm. ADSIF with a $\Delta Z = 100\,\mu$m resulted in a geometric accuracy of 0.88 mm. These two ADSIF processes act as references to which the geometric accuracy of DSIF and MDSIF processes is compared.

For DSIF, at the same value of squeeze factor s ($s = 1.0$, 0.9, 0.8), smaller incremental depths ($\Delta Z = 25\,\mu$m) result in slightly improved geometric accuracy of the formed part. The geometric accuracy is improved by 4.6% for $s = 1.0$, 7.8% for $s = 0.9$, and 13.7% for $s = 0.8$. Furthermore, for a squeeze factor of $s = 0.75$, a similar reduction in the incremental depth results in a significant improvement (62%) in the part accuracy, as compared to the same reduction in incremental depth at a large squeeze factor as mentioned before. It can be seen that in DSIF, with the decrease of the squeeze factor, the influence of the incremental depth on the improvement in geometric accuracy becomes greater. However, even for the best case in DSIF (at $\Delta Z = 25\,\mu$m, $s = 0.75$), the geometric deviation is still larger than that achieved by the pure ADSIF strategy with $\Delta Z = 100\,\mu$m, while the forming time is three times greater (Table 2).

In MDSIF, a reduction in s (from 1.0 to 0.8) at a constant incremental depth (in the 80–120 μm range) causes a reduction in the geometric deviation. According to the previous work [36], with a reduction in the squeeze factor in the D-stage, the forming forces on the bottom tool are higher for a longer duration during the forming process, which mitigates the issue of loss of contact between bottom tool and sheet. This better contact is able to ensure that the D-stage fulfills its purpose of forming the finer geometric details of the part. With the same s value ($s = 1.0$, 0.9) used in the D-stage, the part accuracy increases with a reduction in incremental depth from 120 μm to 80 μm. In fact, for a squeeze factor of 0.8, incremental depths of 80 μm and 100 μm achieve similar and better accuracy, respectively, than the ADSIF toolpath with an incremental depth of 25 μm. At the same time, with an incremental depth of 100 μm the forming time of MDSIF is reduced by 50% as compared to the ADSIF performed with $\Delta Z = 25\,\mu$m. Thus, MDSIF can simultaneously reduce the forming time and the geometric deviation as compared to ADSIF and DSIF if the squeeze factor s can be tuned properly.

The depth of the DSIF formed part shows an obvious deviation from the desired depth, as shown in Figs. 7 and 8, highlighting the disadvantage in geometric accuracy of DSIF as compared to the ADSIF and MDSIF processes. Therefore, ADSIF is able to offer a preformed shape that is closer to the desired geometry than DSIF. DSIF, where the tools move along the desired geometry rather

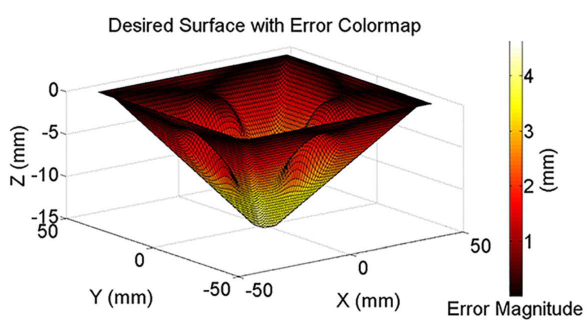

Fig. 8 3D error distribution for a part formed by DSIF $\Delta Z = 100\,\mu$m, $s = 1.0$

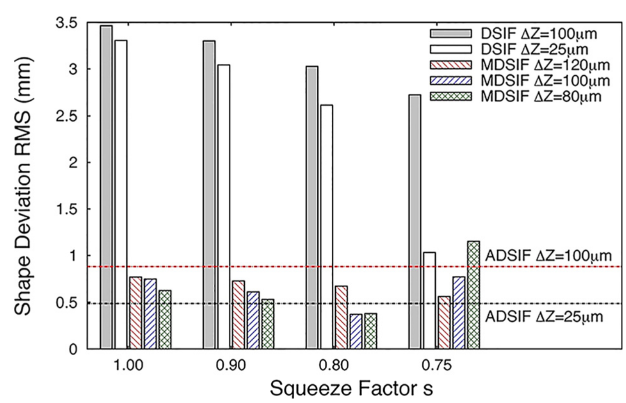

Fig. 9 Experimentally measured geometric deviation

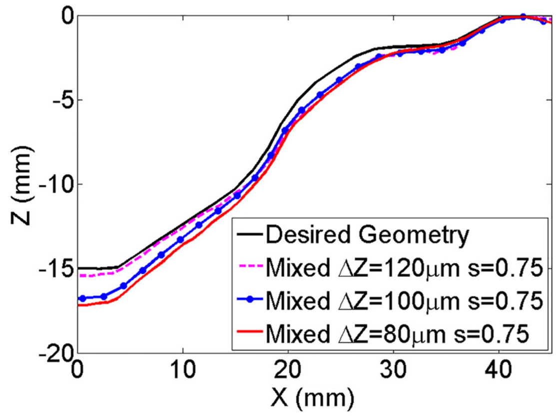

Fig. 10 Geometries formed with squeeze factor $s = 0.75$ with various incremental depths

than staying in-plane as in ADSIF, is capable of tuning the preformed shape. The combination of the two toolpath strategies in MDSIF is able to improve the geometric accuracy.

It should, however, be noted that a special case is observed when a squeeze factor of $s = 0.75$ was used in the D-stage of MDSIF (Fig. 9). Reducing the incremental depth reduces the geometric accuracy, which is opposite to the well-adopted understanding observed in other cases. An examination of the cross section profiles on the inner surface of the formed geometries (Fig. 10) shows that the final geometric features are deeper than desired and the depth increases with the decrease of the incremental depth. This situation was never observed for other squeeze factors. In the D-stage of MDSIF, the vertical travel limit of the tools is the desired depth; however, in the current case, deeper-than-designed final part was observed in MDSIF with small squeeze factors. It is believed that due to volume conservation, additional material was pushed down when the sheet was excessively thinned by over-squeezing during the D-stage, causing an undesired downward rigid body translation of the part which is already formed in the previous stage.

3.2 Thickness Profiles. To nondestructively obtain the thickness profiles over the entire parts, a Romer Absolute Arm with an integrated laser scanner was used to scan both the internal and external surface at one run. The thickness was then obtained by using the same method with calculating the geometric error which is shown in Fig. 7. This method also has the potential to reconstruct 3D thickness map of the parts being investigated. The theoretical thickness distribution of the desired geometry predicted by the sine law [11] and the thickness profiles of three different processes along the same cross section ($Y = 0$) were given in Fig. 11. The irregular oscillation of the thickness profiles was likely caused by the inaccuracy (30 μm) of the laser scanner.

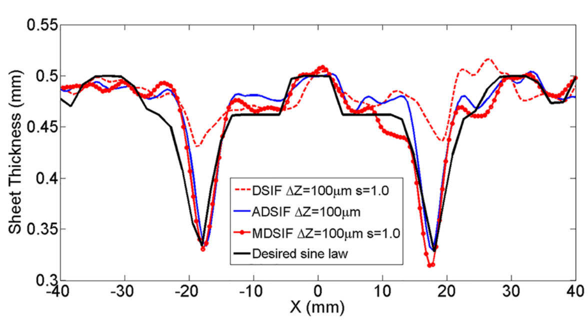

Fig. 11 Thickness profiles along cross section of parts formed by different processes

From Fig. 11, the thickness profile of DSIF deviates from the theoretical calculation using the sine law. On the contrary, the sheet thickness profiles of the parts formed by ADSIF and MDSIF processes are closer to the sine law curve. Therefore, ADSIF and MDSIF (with proper squeeze factors) processes have more predictability in the thickness profile. Although the advantage of MDSIF over ADSIF cannot be indicated by Fig. 11 because of the measurement accuracy, MDSIF outperforms ADSIF in geometric accuracy as discussed in Sec. 3.1.

4 Conclusion

The MDSIF strategy, proposed in this work, aims to improve the geometric accuracy while reducing the forming time. The performances of ADSIF, DSIF, and MDSIF with different incremental depths and squeeze factors were experimentally compared. It was observed that increasing the incremental depth or the squeeze factor has negative effect on part accuracy in DSIF. Furthermore, MDSIF with $\Delta Z = 100\,\mu$m and $s = 0.8$ was shown to be able to achieve a better geometric accuracy than the previous best achievable geometry that is obtained by ADSIF with $\Delta Z = 25\,\mu$m, while reducing the forming time by 50%. When $0.8 \le s \le 1.0$ in MDSIF, decreasing the magnitude of the squeeze factor leads to increased geometric accuracy. When $s = 0.75$, the MDSIF formed parts are deeper than the desired depth and the formed parts become larger with the reduction of the incremental depth. This indicates that an optimum value of s exists for a given incremental depth.

This work has provided a novel and promising incremental forming process, which has the capability to reduce the manufacturing time as well as to improve part quality. Therefore, this new cost-efficient process has great potential to increase the forming throughput yield.

The squeeze factors in this paper were chosen without the consideration of machine compliance and tool deflection. Different squeeze factors may apply on different machines. Future work will take machine compliance and tool deflection into account and develop more generalized DSIF parameters. Additional studies on the understanding of the ADSIF process are in progress.

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