Investigation into a new hybrid forming process: Incremental sheet forming combined with stretch forming

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1. Introduction

Asymmetric incremental sheet forming (AISF) has been conceived to enable flexible forming of sheet metal parts based on CNC technology. In AISF, a blank is clamped at its border and progressively deformed by a punch that follows a tool path programme reproducing the final part shape, see Fig. 1. Two main variations of AISF are distinguished: ‘single point incremental forming’ (SPIF) and ‘two point incremental forming’ (TPIF). More details can be found in a recent review paper [1].

As detailed in [2], for a wider industrial use of AISF it is mandatory to find solutions to the main limitations of the process, which are: (i) the long process time, (ii) the sheet thinning, (iii) the limited geometrical accuracy and (iv) the lack of dedicated process planning and modelling tools.

In this paper, a new hybrid process is analysed, the combination of AISF and stretch forming (SF). This new process combination will be motivated in the ‘state of the art’ section by analysing the work that has been done so far to overcome the limitations of AISF. Each of the process limits will be analysed separately, and hypotheses about the benefit of combining AISF with stretch forming will be formulated. The process combination will be analysed in Section 3, which starts with the development of a forming machine that combines AISF and stretch forming. A ‘spherical cap’ with a circumferential groove is used to analyse and compare the hybrid process and the basic AISF process regarding sheet thinning and forming time. Finally, an overview over current developments of dedicated CAX algorithms and finite element models for SF + AISF are given, which are essential steps towards an application of the new hybrid process.

2. State of the art

In this section, the state of the art in AISF and some approaches to overcoming the current process limits of AISF will be briefly summarized:

2.1. Sheet thinning

Thinning in AISF depends on the wall angle \( \alpha \) according to the so-called sine law [2]:

\[
t_1 = t_0 \sin(90^\circ - \alpha)
\]

The definition of \( \alpha \) is given in Fig. 1. For parts with wall angles greater than 60–70°, multistage forming strategies have to be used to avoid excessive thinning [3]. In multistage forming, a pre-form, several intermediate shapes and the final part geometry are formed by AISF. As reported by Hirt et al. [4] a process time of approximately 7 h is required to produce a square box of 200 × 200 mm in 15 forming stages. The intermediate stages had to be found by trial and error. As a consequence, this approach cannot be easily transferred to more complex parts. An improved forming strategy detailed in [4] generates a pre-form by stretching the sheet metal roughly over the male die using AISF with a large step-down. A stiffening brace was manufactured using this strategy [4], but pre-stretching by AISF leads to large forming forces and increases the likelihood of wrinkling, which makes it hard to transfer this approach to other part geometries.

2.2. Geometric accuracy

Recently, Micari et al. [5] have studied the feasibility of some forming strategies that aim at improving the accuracy of parts formed by AISF, identifying tool path ‘overbending’ as a promising approach to improve the accuracy of a part. In contrast, the work detailed in [3] shows that ‘overbending’ induces waves on the formed part, and that a part manufactured by AISF will contain...
considerable residual stresses as a consequence of the cyclic loading and unloading during forming.

2.3. Forming time

AISF is an incremental forming process. The time to manufacture a part is determined by the length of the tool path and the average travelling speed of the forming tool. Bambach [2] shows that the process time required to manufacture a conical frustum of height $h$, bottom radius $r = h$ and top radius $2r$ scales quadratically with $h$: assuming an average speed of 500 mm/s and a step-down of 0.2 mm for the tool path (cf. [2]), the forming time is already greater than 1 day for a conical frustum of 1 m height.

2.4. Finite element modelling

An overview of process models for AISF is given in [1,3]. In particular [3], analyses the CPU time required to simulate the forming of the conical frustum mentioned in the preceding paragraph on a single processor machine using a dynamic explicit code. The FEA takes almost 10 days using tool path with a step-down of 0.5 mm, and more than 20 days with a step-down of 0.2 mm. This makes FEA prohibitive for larger parts.

3. Hybrid AISF: stretch forming + AISF

Although it is not inconceivable that ways will be found in the future to overcome the process limits of AISF and to enable model-based process planning, an alternative process will be analysed in this paper: the combination of AISF and stretch forming. The concept of the new hybrid process is illustrated in Fig. 2, which indicates that stretch forming is used to create a pre-form in a first forming step. Stretch forming will not yield the final part geometry (otherwise the process combination would not be necessary). Hence, features such as pockets, corrugations or grooves that are not formed during SF are formed using AISF.

The statements 1–4 do not hold for arbitrary parts. It will be necessary to identify part geometries for which the process does offer these advantages. Due to the restricted space, only the hypotheses 1, 2 and 4 are tested in this paper. A hemispherical base with circumferential groove is used to analyse the possible benefits of the process combination compared to pure AISF. As detailed above, the machine set-up will be discussed first before the experimental tests are given.

4. Process investigation

4.1. Experimental set-up

Fig. 3 shows an AMINO DNLC-RB forming machine in which the original hydraulic control system of the frame was replaced by four screws jacks driven by a servo motor. The screw movements are controlled by a closed-loop control system. With this set-up, a downward force of 50 kN can be exerted in order to perform stretch forming experiments on soft materials, e.g. aluminium alloys.

4.2. Experimental tests

As mentioned above, a hemispherical part with circumferential grooves serves as benchmark part for the analysis of the sheet
thinning induced by the combined process. Two experiments will be presented:

1. The forming of a section of a hemisphere without pockets was considered in order to analyse the differences in material flow induced by AISF and SF. The aim was to analyse sheet thinning using a simple part for which both AISF and stretch forming can be treated analytically.

2. The forming of a section of a hemisphere with a groove around the circumference is analysed to show the benefit of the process combination of AISF and SF compared to pure AISF both in terms of sheet thinning and forming time.

A cap of a hemisphere was formed by AISF and by stretch forming using a die of 240 mm radius and 1 mm AA1050-O sheets. The forming depth was 25 mm, which was sufficient to show the different thinning behaviour of AISF and SF. The measured thickness distributions are given in Fig. 4. The sheet thickness in AISF decreases in radial direction with increasing wall angle, in accordance with the sine law, Eq. (1).

Sheet thinning in stretch forming over a hemispherical punch has been analysed e.g. in [7]. Under frictionless conditions, the maximum amount of thinning occurs at the pole. With non-zero friction, the maximum thinning can be found at a certain distance from the pole. After the maximum, the sheet thinning drops in radial direction, which is in contrast to the course of sheet thinning obtained by AISF. Two conclusions can be drawn from this result:

1. Stretch forming can be used to induce thinning in areas that would not be deformed by AISF, in this case in the pole. Hence, the combination of AISF and SF offers the possibility to achieve a more homogeneous thickness distribution compared to either SF or AISF.

2. There is a certain point along the radius where AISF and SF induce the same amount of thinning. Beyond that point, less thinning is generated by SF than by AISF. If a pocket is lying beyond that point, more material would be available to form the section. Both for AISF and SF + AISF, the maximum thickness reduction was measured in the groove. The maximum measured thinning is smaller for SF + AISF and the distribution of the thickness along the section is more uniform than in the case of pure AISF.

It is worth mentioning that the stretch forming unit does not offer enough force to manufacture a complete hemisphere by stretch forming of steel sheets. Hence, only a spherical cap was considered, and the groove had to be placed in an area where the advantage of the process combination is not overly pronounced.

4.3. Process modelling

A finite element model was set-up in LS-DYNA for the forming of the grooved sphere both for pure AISF and the combined process. In the FE model for SF + AISF, the sheet was meshed with 13,500 shell elements for the first forming stage, i.e. the stretch forming. Automatic remeshing was applied in the AISF forming step which yielded approximately 30,000 elements at the end of the simulation. The CPU time for the simulation of the stretch forming step was 2 h, while the simulation of the forming of the groove took approximately 6 days on a two processor machine. Fig. 6 shows the distribution of major surface strains measured on the formed part using a ‘gom ARGUS’ system in comparison with the numerical results.

The numerical and experimental results show a similar deformation pattern. The comparison of the results along a radial section line in Fig. 7 shows that the FEA predicts well the strains found in the experiment.

In the simulation of pure AISF, a fine mesh with 30,000 elements has to be used from the beginning. Due to the length of the tool
path, 39 days were needed to simulate the whole AISF process. Fig. 8 shows a comparison of measured and simulated major strains along a radial section, similar to Fig. 7. Trials showed that the simulation cannot be sped up by applying more mass scaling or using less elements without losing accuracy.

The results show that SF + AISF has the advantage that the simulation of the stretch forming can be completed in a relatively short time, even for a larger part, which makes it possible to simulate and optimise at least the first forming stage.

4.4. CAX development

In order to save time through the process combination of AISF and SF compared to pure AISF, the time needed for the stretch forming and the time needed to form the remaining features using AISF must be minimised. However, the areas $G$, $G_P$ and $G_P$ shown in Fig. 2 are not known a priori, but are the result of the stretch forming operation and the springback after forming. For a minimum forming time per part, it is necessary to identify the regions which have to be formed by AISF. Since the prediction of the part shape after SF concerning the thickness distribution and geometry is not possible analytically for complicated shapes, the utilisation of FEA is indispensable.

To detect the sections that need AISF processing, the process chain depicted in Fig. 9 was developed, which enables to optimise the process time and provides the NC-codes for both SF and AISF. First, the target part is transferred to Unigraphics NX. With NX, the NC-path for SF is generated and transferred to LS-DYNA. The stretch forming simulation in LS-DYNA yields the part geometry and sheet thickness distribution. This information is transferred back to NX. An algorithm that detects deviations between the simulated geometry and the target geometry was implemented in UG NX. This algorithm identifies the areas that need to be deformed by AISF and creates the NC-path programmes for the forming of these areas. This approach was used to optimise the tool paths for the benchmark part. The forming time using AISF was 35 min, which could be reduced to 20 min in the combined process.

4.5. Summary and outlook

A new hybrid process, the combination of AISF and stretch forming was put forward and investigated in this paper. It can be concluded that with the process combination of AISF and SF:

- A noticeable reduction of production time compared to AISF is possible, especially when the areas that need to be processed by AISF are identified in advance.

Future research will focus on the effect of the process combination of SF and AISF on the geometrical accuracy and the forming limits. The latter is important when part features such as pockets have to be formed from a pre-stretched sheet. From an application point of view it seems important to consider industrial parts in the future.

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