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Investigation of a Hybrid Process: Multipoint Incremental Forming

Safa Boudhaouia, Mohamed Amen Gahbiche, Eliane Giraud, Wacef Ben Salem, Philippe Dal Santo

***Abstract*—**Multi-point forming (MPF) and asymmetric incremental forming (ISF) are two flexible processes for sheet metal manufacturing. To take advantages of these two techniques, a hybrid process has been developed: The Multipoint Incremental Forming (MPIF). This process accumulates at once the advantages of each of these last mentioned forming techniques, which makes it a very interesting and particularly an efficient process for single, small, and medium series production. In this paper, an experimental and a numerical investigation of this technique are presented. To highlight the flexibility of this process and its capacity to manufacture standard and complex shapes, several pieces were produced by using MPIF. The forming experiments are performed on a 3-axis CNC machine. Moreover, a numerical model of the MPIF process has been implemented in ABAQUS and the analysis showed a good agreement with experimental results in terms of deformed shape. Furthermore, the use of an elastomeric interpolator allows avoiding classical local defaults like dimples, which are generally caused by the asymmetric contact and also improves the distribution of residual strain. Future works will apply this approach to other alloys used in aeronautic or automotive applications.

***Keywords*—**Incremental forming, numerical simulation, MPIF, multipoint forming.

I. Introduction

CONVENTIONAL shaping techniques such as stamping and hydro forming generally require specific tools depending on the type and form of the desired piece. Therefore, these manufacturing processes are not recommended for single, small, or medium series production. In order to overcome this issue, several flexible processes have been developed for these last decades, as for instance the ISF and the MPF processes.

The MPF is a recent flexible technique for sheet metal's manufacturing. In this process, the conventional punch and die in the drawing process are replaced by a pair of opposed matrices which are both made up of a set of adjustable pins. This manufacturing process is very flexible since it allows the production of three dimensional parts with different geometry, only by adjusting the punches' height, which results in a great saving of time and manufacturing costs particularly for small and medium lot or single production [1]-[3]. The industrial applications of MPF include multiple domains such as the civil engineering, transportation industry, medical engineering, and so on. For instance, MPF has been used for the manufacture of steel structure for Bird's Nest Stadium, skins for aerospace panels, high speed train body, and architectural facades [3]. On the other hand, ISF is another new flexible forming process that consists of locally deforming the metal sheet in order to progressively bring it to the desired final shape. It has been noticed that the material formability during ISF process is largely improved in comparison with conventional shaping techniques [5]. There are mainly two types of incremental forming as illustrated in Fig. 1: Single point incremental forming (SPIF) where no matrix is needed and two-points incremental forming (TPIF) where a partial or complete conformational system is used.

In TPIF, the sheet is clamped around its edges with a blank holder that moves vertically. Therefore, the final shape of the part is mutually obtained by the tool trajectory and the shaping matrix. On the other hand, it has been noticed that the geometric accuracy of a sheet part produced using TPIF is better than that of a similar part obtained by SPIF [4], [6]. However, this type of process is not considered as much flexible as the SPIF since a new die is needed for producing each new part, as unconventional sheet metal forming.

The two techniques mentioned above remain limited in terms of shape, geometric, and dimensional accuracy. In terms of flexibility, the first technique gives wider perspective than the second one.

II. MPIF

A. Presentation of the New Hybrid Process (MPIF) and the Experimental Set Up

In order to benefit from the enhancement of the geometric accuracy offered by the TPIF and to overcome the necessity of a new die for manufacturing each new part, which is the major disadvantage of this process, an experimental prototype was designed and tested by authors (Fig. 2). This testing device consists of two parts inspired of the two original processes earlier described. The upper part is the rotating forming tool, controlled by a predetermined program on a CNC machine as in conventional ISF process. The lower part is the reconfigurable die whose principle derives from the MPF. Hence, an innovative hybrid new process with an unlimited flexibility is created: The MPIF process.

To justify the feasibility of the new process and to explore its potentialities, we have designed the tool defined in Fig. 2. This device's overall dimensions are 170×95×150 mm^3. It is composed of a lower assembling flange carrying 80 rectangular pins with rounded end. The clearance between the

S. Boudhaouia is with the Mechanical Engineering laboratory, National Engineering School of Monastir, Tunisia (Phone: 216-98 34 80 69; e-mail: sa.boudhaouia@gmail.com).

M. A. Gahbiche and W. Ben Salem are with the Mechanical Engineering laboratory, National Engineering School of Monastir, Tunisia (e-mail: amen_gahbiche@yahoo.fr, wacef.bensalem@gmail.com).

P. Dal Santo and E. Giraud are with The ENSAM Campus d'Angers, France (e-mail: Philippe.DalSanto@ensam.eu, Eliane.giraud@ensam.eu).

different pins is adjusted by two clamping plates controlled by screws. The sheet metal is blocked by two blank holders having the possibility of vertical motion thanks to two guiding columns. All the experimental set up is mounted on a 3-axis CNC vertical milling machine where the experimental tests are carried out.

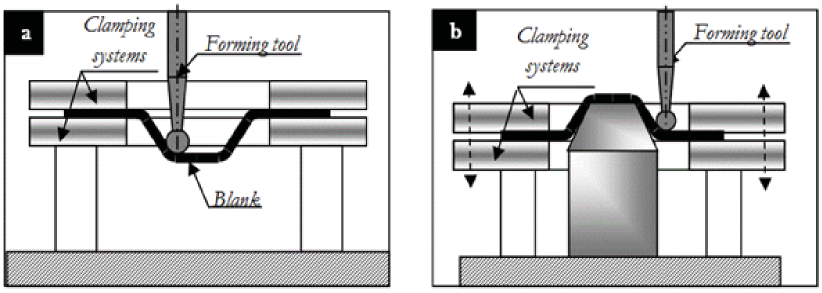

Fig. 1 ISF categories: (a) SPIF (b) TPIF [7]

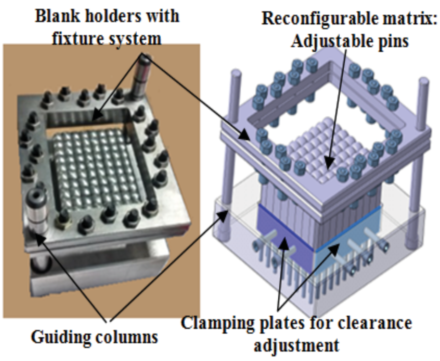

Fig. 2 Experimental set up of the MPIF process

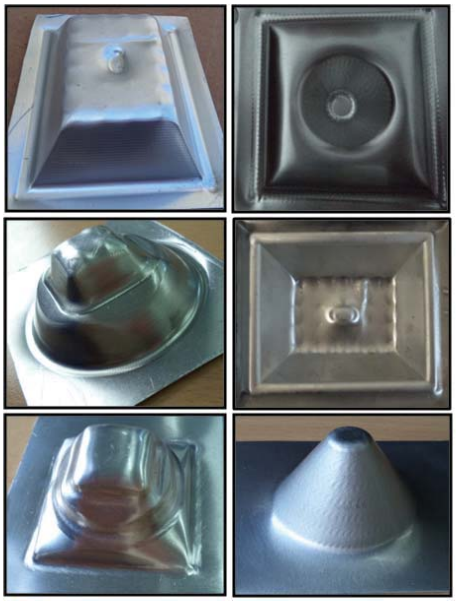

Fig. 3 Parts manufactured using the MPIF process

B. Experimental Investigation

Several shapes have been performed in order to test the feasibility of the MPIF. Some of the manufactured parts are presented in Fig. 3.

The experimental tests were performed on aluminium alloy sheets (Al 1050A). The flange's initial dimensions are 170×150×0.6 mm^3. Its mechanical characteristics are listed in Table I. The manufactured parts have been obtained by using an 8 mm diameter hemispherical tool. The punches' height is adequately adjusted in order to obtain the satisfactory shape of the global die which will determine the final part's shape.

The effect of the punches' rounded tips can be obvious on some of these obtained products. This phenomenon is generally known as "dimples" and it is an inevitable defect during the MPF process [1].

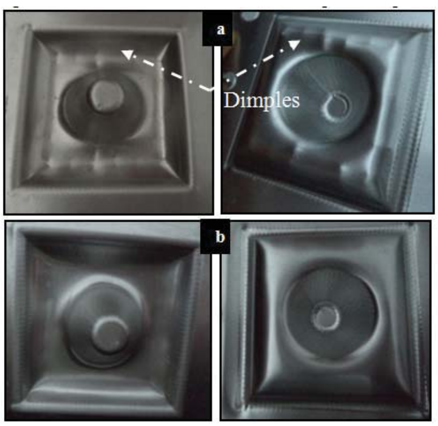

Fig. 4 (a) Parts without an interpolator, (b) Parts with a 2mm interpolator

As a matter of fact, during the forming phase, the sheet metal is subjected to an extremely concentrated pressure induced by the action of the forming tool associated with the lower punches' extremities. Several studies have shown that the use of an elastic stack called interpolator improves the contact between the blank and the discrete matrix and thus reduces and even eliminates the dimpling phenomena. Furthermore, when the thickness of the interpolator increases, the sheet's thickness is more homogeneous and deformations are much evenly distributed [8]. These findings were also confirmed for the MPIF process. Two parts were manufactured by using the same tool path trajectory. The only difference is that for the second one, a 2 mm elastomeric stack was added between the sheet and the punches. A remarkable improvement of the final part's quality has been noticed since all the dimples are almost suppressed. The two manufactured parts are shown in Fig. 4.

TABLE I
1050a ALLOY PROPERTIES [7]

Young's modulus	Poisson's ratio	A%	R_m	r_0	r_{45}	r_{90}
E=69 GPa	ν=0.3	27	115	1.79	2.45	1.7

III. NUMERICAL SIMULATION OF MPIF PROCESS

A. Model Presentation

Finite element numerical simulation is widely used in the field of sheet metal forming. This method is very beneficial because there is no need for costly experiences to characterize the sheet metal's deformation, the stress and strain distributions.

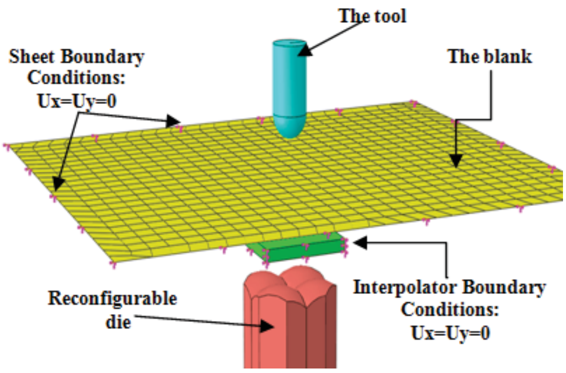

Fig. 5 Numerical model of the MPIF process

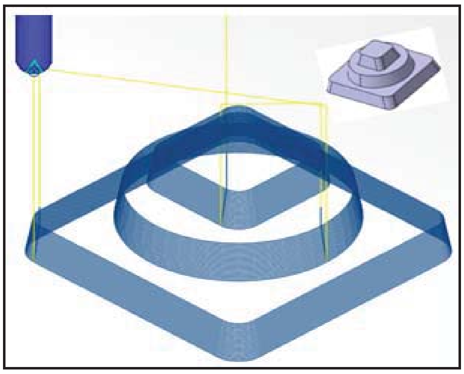

Fig. 6 Toolpath trajectory

In our case, ABAQUS/Explicit was used for Finite Element (FE) analysis of the MPIF process.

Fig. 5 shows the assembly of the deformable flange, the forming tool and the punches of the discrete die. The aluminium flange is meshed by using linear shell elements considering reduced integration (S4R) with five integration points through the thickness. In this primary approach, after a sensitivity analysis balancing CPU time to precision, the global mesh size is fixed to 2 mm × 2 mm for the shell elements of the sheet. The forming tool is modelled by an analytic rigid surface and controlled through its reference point. The assembly of the different punches forming the lower die was elaborated by using the CAD software CATIA and then imported to the FE model. Surface to surface contact with hard contact and Coulomb friction are used for the interaction between the forming tool (master) and the sheet (slave). A global friction coefficient of μ = 0.1 is chosen for this contact property. The same type of interaction is also considered to describe the contact between the blank and the die.

When the interpolator is used, the proper interaction between this elastomeric stack and the flange and also between the die and the interpolator are considered. The friction coefficient is chosen as μ = 0.2 at the interface punches/interpolator and μ=0.1 for interpolator/blank [9]. The elasto-plastic material model with anisotropic hardening was used for the deformable sheet [7]. As for the elastomeric interpolator, the Mooney–Rivlin hyper-elastic material model was used with the same properties as those defined in [10].

The simulation process is organized in three steps: approach, forming, and retraction. During the forming step, the tool which is controlled by its reference point follows the toolpath trajectory that has been generated by CAM software. The conversion of this trajectory into boundary conditions is done automatically through a python script as detailed in [7]. The motions of the sheet's exterior edges have been all blocked except for the translation along the z axis which has been kept free to replicate the experimental conditions.

B. Results and Discussion

The tested part has a relatively complex geometry. The corresponding toolpath is presented in Fig. 6. The forming tool starts by forming the upper box having a 10 mm height, and then it moves to the middle 10 mm cylinder to finally form the lower box. The overall height of the part is 30 mm. The supporting die in this case of study is constituted of four punches as detailed in Fig. 5.

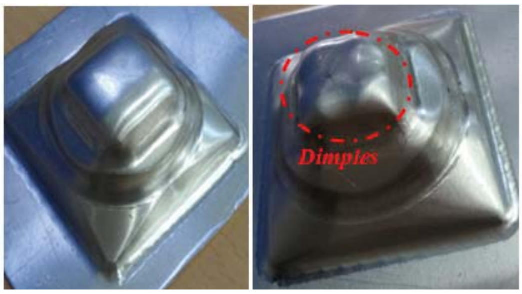

Fig. 7 Influence of the elastomeric interpolator

The influence of the elastomeric interpolator can be clearly seen in Fig. 7. In fact, the upper surface of the piece formed by interposing an interpolator between the sheet metal and the die is obviously more regular and smoother. This was also confirmed by numerical simulations. In fact, Fig. 8 (a) describes the part's final profile along the middle section (along the plan Y =0). A zoom of the final part's upper area, which has been in contact with the lower punches of the reconfigurable die during the whole forming operation, is detailed in Fig. 8 (b). This surface is clearly dimpled in comparison with the surface of the part formed with the addition of the electrometric interpolator. Hence, the findings of the interpolator's contribution during the classical MPF remain also valid for the MPIF process. As a conclusion, the addition of elastomeric layers reduces the dimpling defect and improved the profile regularity and the surface quality.

Another interesting role of the interpolator can also be deduced from Fig. 8: The spring back effect is less pronounced in the presence of the interpolator. The part's geometry is improved in the latter case and it is consequently more close to the desired shape. In addition, the residual stress distribution is also more homogeneous (as detailed in Fig. 9) which may explain the spring back reduction. These last numerical results need to be further investigated and experimentally validated by 3D control and measurement system.

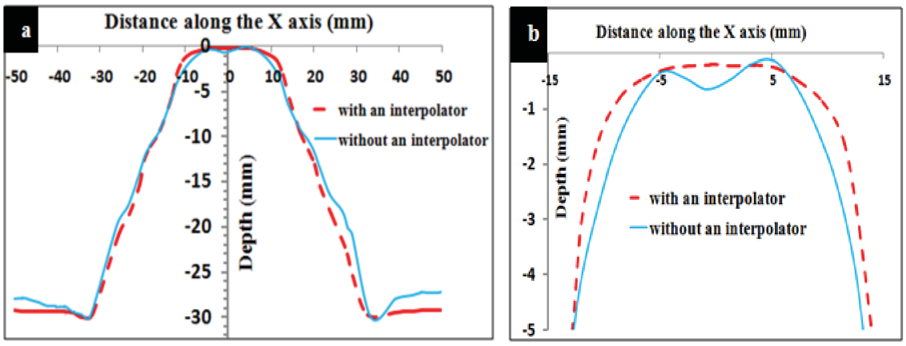

Fig. 8 Influence of the elastomeric interpolator

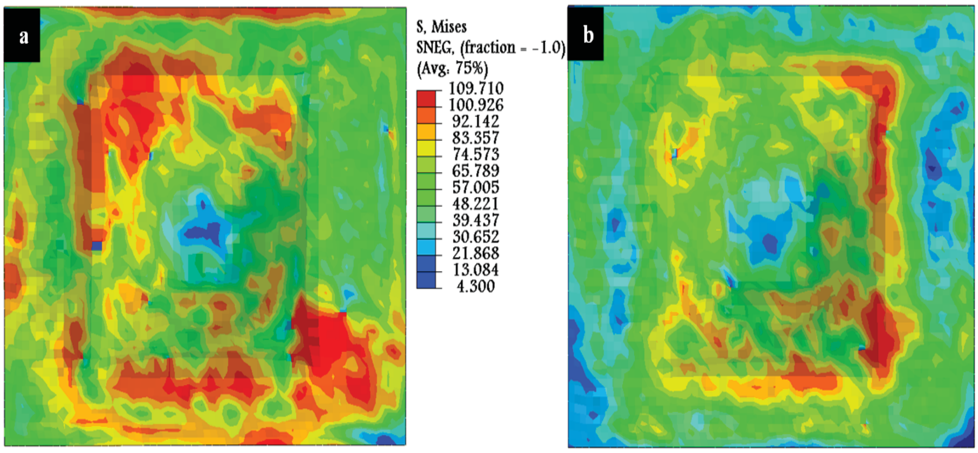

Fig. 9 Stress distribution in the part (a) without an interpolator (b) with an interpolator

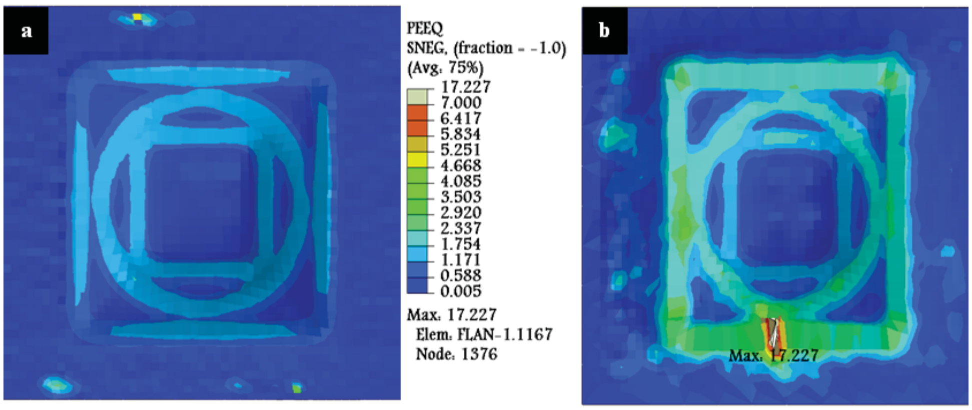

Fig. 10 Equivalent plastic strain distribution PEEQ (a) with an interpolator (b) without an interpolator

The deformation induced on the deformed part when an interpolator is used, is substantially homogeneous on all the areas that are supposed to be heavily deformed. The maximum recorded value in this case is around 1/10 of the maximum value recorded for a part without an interpolator addition (see Fig. 10).

When the interpolator is absent, the plastic equivalent strain distribution is less homogenous and presents a peak corresponding to the last steps of the forming operation. The maximum value recorded in this particular regard, encourages a more thorough investigation. Given these results coupled with those of the stress distribution, the optimization of the MPIF's parameters is strongly recommended, as for instance the optimum thickness of the interpolator, the minimization of the friction between punch - sheet, the tool federate, and so on.

IV. Conclusion

A new hybrid process combining the MPF and TPIF processes was investigated in this paper. Its feasibility was validated by using a prototype designed and realized by authors. Successful standard and complex products were successfully obtained by using this process. The main advantages of the MPIF are its great cost saving especially for small batch or single production in addition to the wide range of products that could be manufactured by using this process. The main geometrical defect in the fabricated parts is the dimples; a defect causes by the pins tips. Through the introduction of an elastomeric interpolator between the reconfigurable die and the sheet, this defect could be reduced and even eliminated.

Future research will focus on the effect of the process on the enhancement of the geometrical accuracy and the forming limits. The numerical model will be also developed by the introduction of the appropriate damage law in order to predict the failure of the part.

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