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Experimental and numerical study of a new hybrid process: multi-point incremental forming (MPIF)

Safa Boudhaouia¹  · Mohamed Amen Gahbiche¹ · Yessine Ayed² · Eliane Giraud² · Wacef Ben Salem¹ · Philippe Dal Santo²

Abstract

Multi-Point Incremental Forming (MPIF) process is a new hybrid process that combines two common manufacturing methods. These are Multipoint Forming (MPF) and Incremental Sheet Forming (ISF) processes. In this study, an experimental set-up, based on a MP reconfigurable die, was designed and manufactured to explore the flexibility of this innovative process and its potentialities to produce complex parts using the same tools. The obtained results have indicated that this novel technique, that doesn't require costly equipments, is an effective approach to manufacture multitude of parts with different shapes. Moreover, it has been shown that the parts geometrical accuracy as well as thickness distribution are enhanced compared to the conventional ISF process and that the geometrical defects, called 'dimples' and caused by the pins' ends, are significantly reduced and almost eliminated after the insertion of a rubber piece between the reconfigurable die and the blank sheet. On the other hand, the effect of the size and geometry of the rectangular pins on the geometrical accuracy and the dimpling defect has been studied using a finite element analysis.

Keywords Incremental forming · Multipoint forming · Hybrid process · FEA · Geometrical accuracy · Thickness distribution

Introduction

Flexible sheet forming processes have lately drawn significant interests for both academic researches and industrial applications. The biggest advantage offered by such techniques is the reduction of tool costs especially when small batched or single customized parts' manufacturing is planned. Moreover, unlike conventional processes, the production of dissimilar shape parts using flexible forming techniques don't require the use of different dies which involves a long time to manufacture the needed tools and a considerable storage space once utilized. In this context, Multi Point Forming (MPF) and Incremental Sheet Forming (ISF) processes are both among the most well known flexible sheet forming techniques.

In MPF process, whose concept was first proposed by Nakajima [1] in the 1970s, the traditional rigid punch and die of the conventional drawing process are replaced by two opposed matrices composed of many movable pins [2]. As a result, three dimensional surfaces can be obtained by adjusting the height of each individual pin. Despite its high flexibility, this technique conceals a major geometrical defect, known as 'dimples' taking place on the surface of the final part and caused by the irregular contact between the sheet and the pins tips. In the open literature, several authors have succeeded to reduce and even eliminate his defect [3, 4]. As a result, the use of this process in multiple industrial applications such as civil engineering, medical engineering, the transportation industry, architecture, etc. was encouraged [5].

ISF is also a very interesting flexible process. It's based on local incremental deformation. The part is progressively formed using a small diameter hemispherical tool that follows a predetermined trajectory usually generated by CAM software. Although this process was patented in an earlier time [6], it didn't gain a serious attention in the academic community until the 1990s, as a result of the development of the NC technology [7]. Many researchers have studied the influence of the process's parameters (such as the tool diameter, the wall

✉ Safa Boudhaouia
sa.boudhaouia@gmail.com

¹ Mechanical Engineering Laboratory, National Engineering School of Monastir, University of Monastir, Monastir, Tunisia

² LAMPA, Arts et Métiers ParisTech, 2 boulevard du Ronceray, 49035 Angers, France

angle, the material properties, the toolpath strategies, etc.) on the material formability, the surface roughness and the forming forces [8–10]. Despite its high flexibility and improved formability compared to conventional processes, ISF suffers from a major drawback which is the poor geometrical accuracy and the non uniform thickness distribution. In order to overcome these problems and thus stimulate the process industrialization, other ISF variants have been developed such as multi-step incremental forming, two-point incremental forming (TPIF), double-sided incremental forming (DSIF) and accumulative double-sided incremental forming (ADSIF) processes. For example, [11] have reported a higher geometrical accuracy when TPIF is used, but have also noted a low flexibility because of the need of a proper die for each new part.

Hybrid manufacturing, which consists in combining two or more manufacturing techniques, can offer solutions to some limitations of the original processes and enhance their distinctive advantages. As a result, a more efficient process is created. Lately, great efforts have been deployed to investigate different hybrid processes. For instance, [12] have indicated that a better thickness distribution and a significant production time reduction can be obtained by combining both of ISF and stretching processes. However, that hybrid process, as in the case of TPIF, requires a specific supporting die when a new geometry is considered. In a more recent work, [13] have combined the MPF and ISF techniques to create a new two-step hybrid process. The first process was used as a preforming step, before conducting the incremental sheet forming operation. Accordingly, these authors have noted that a more uniform thickness distribution can be obtained, provided that an optimal preform is chosen. However, given the designed device, the developed process doesn't allow the manufacturing of parts with negative curvature (such as concave pockets) since the second step (ISF operation) necessitates the rotation of the blank holder.

In the present work, a new hybrid process called Multi Point Incremental Forming (MPIF) is proposed. It combines the MPF and ISF technologies. Unlike the two-steps MPIF process [13] previously discussed, our formed parts are simultaneously obtained by the action of the ISF toolpath and the MPF reconfigurable die. It is foreseen that the product thickness distribution and geometrical accuracy would be improved compared to ISF thanks to the use of the MP reconfigurable die. Moreover, complex parts that were not possible to obtain separately by either of the original processes are expected to be manufacturable using the new proposed technique. The principles of this new technique were first described by [14, 15]. However, only a simple spherical shape was presented and manufactured using this technique [14], which doesn't reveal the process's actual potentialities. So, in order to prove the feasibility of this process and investigate the validity of its proclaimed benefits, an experimental set up

has been implemented and some of the manufactured parts will be presented. Furthermore, in order to compare our results to those obtained using the conventional incremental sheet forming technique, a standard geometry (a truncated pyramid) is manufactured. The experimental results will then be compared to numerical ones obtained using the commercial finite element analysis software Abaqus. In addition, a complex part with a concave feature has been also manufactured. This geometry which is impossible to manufacture using the conventional ISF technique, was essentially chosen in order to emphasize the flexibility and the advantages of the new process. On the other hand, the insertion of a rubber piece between the lower reconfigurable die and the blank sheet has considerably improved the surface quality of the parts formed using the MPIF process by reducing the geometrical defect called dimples which was caused by the rectangular pins' ends. Finally, the effect of the size and geometry of the die pins was numerically investigated.

Presentation of MPIF process

Description of the MPIF experimental set up

Our new MPIF device is presented in Fig. 1. Its overall dimensions are $170 \times 150 \times 160 \text{ mm}^3$. It essentially consists of two main parts. The lower part is the reconfigurable die, deriving from the MPF technology, and it is composed of a lower support carrying 80 adjacent $10 \times 10 \times 70 \text{ mm}^3$ rectangular pins with 10 mm radius tip. The interior volume of this pins support (where the pins will be assembled) is $\approx 105 \times 95 \times 45 \text{ mm}^3$. Two clamping plates ensure the adjustment of the clearance between these pins. Each pin's height is controlled by a corresponding lower screw. As in the TPIF process, the blank sheet is fixed by two blank holders that freely slide down four guiding columns. The upper part, on the other hand, is an 8 mm diameter hemispherical forming tool, attached to the CNC spindle and moving according to a predetermined trajectory generated by CAM programs, as in the case of the conventional ISF process. The different forming operations are conducted on a 3-axis CNC vertical milling machine. More technical specifications are reported in Fig. 1.

Effectiveness and flexibility of MPIF

Using the manufactured MPIF device, different shapes have been successfully formed. Some of them are presented in Fig. 2. In fact, since the lower multi-point die is reconfigurable, no specific expensive dies were required, which highlights the flexibility of MPIF. Moreover, the use of a single stage forming operation instead of two separate steps (a first preforming MPF step and a second ISF step) makes it possible to manufacture parts with intricate geometry

Fig. 1 Experimental set up

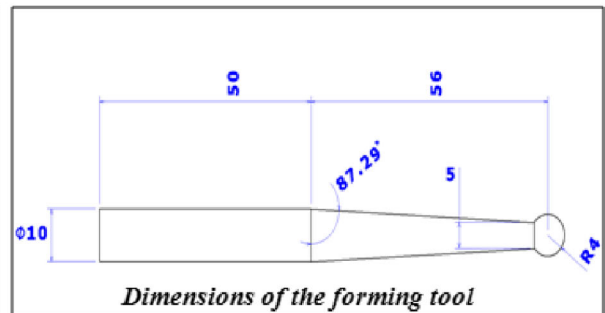
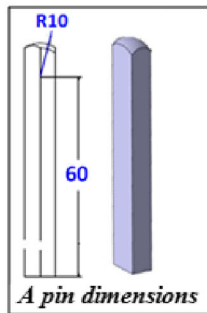
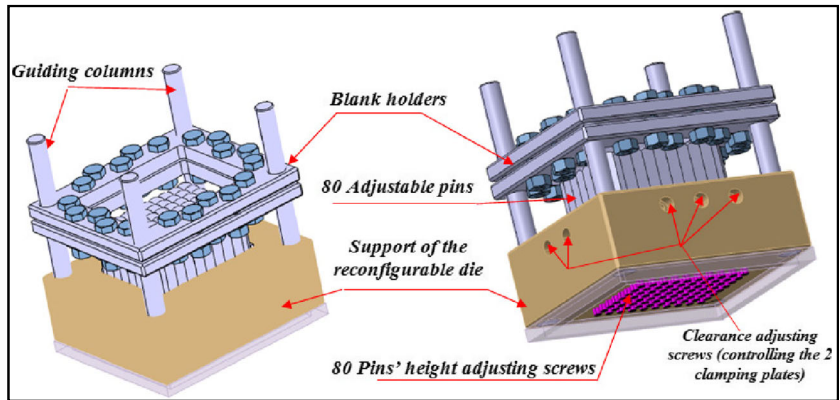
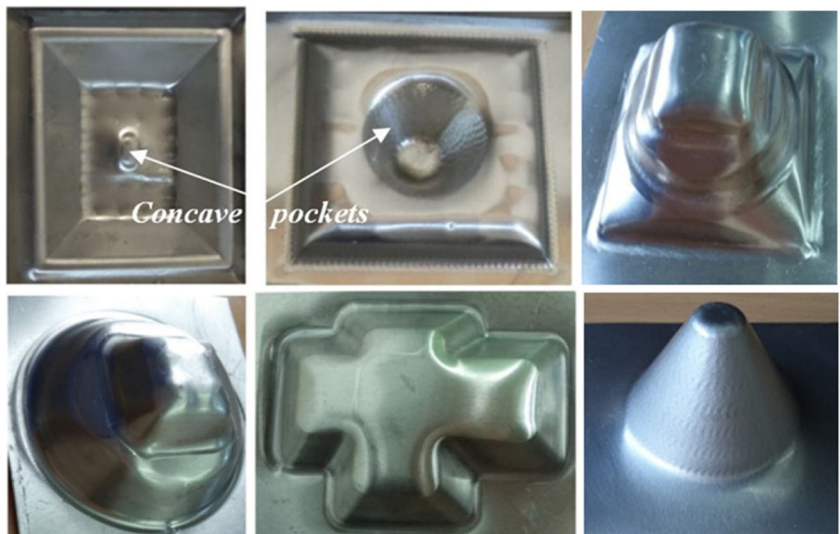


Fig. 2 Sample of parts created using the MPIF set up



and negative curvatures which is not possible using conventional ISF and two-step hybrid MPIF processes. Two different manufactured parts will be further analyzed in the next section: the first one is standard pyramidal part and the second is a part with a complex geometry. Despite the enormous geometric dissimilarities of these two parts, they were both obtained using the same reconfigurable die only by adjusting the height of the rectangular pins accordingly to the CAD model. A sample of the die configurations and the corresponding manufactured parts is shown in Fig. 3.

Hybrid process investigation

Material of the formed parts

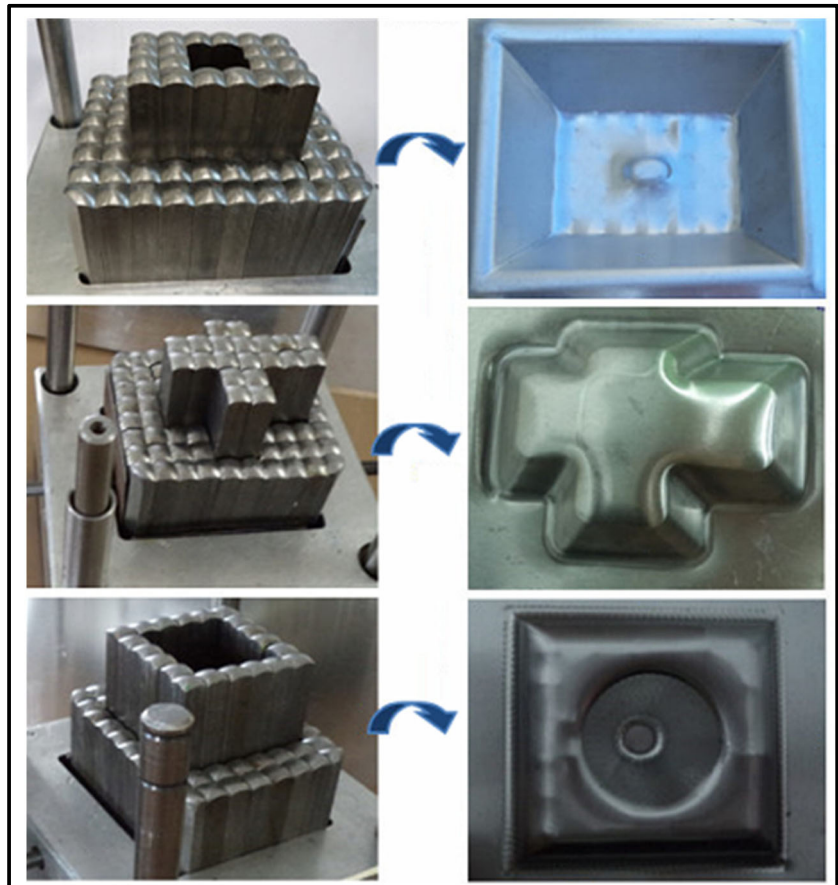
In this study, all the forming experiments were carried out on aluminum alloy sheets (Al 1050A), having a thickness of 0.6 mm. Since such material generally exhibits high plastic anisotropy, tensile tests were conducted on specimens with grain orientations along the rolling, diagonal and transverse (0° , 45° and 90°) directions. As can be noted in Fig. 4a, the deviation between the three curves is quite significant which underlines this material's anisotropy. Moreover, this alloy

exhibits a moderate ultimate strength and a high elongation percent at break which is very interesting for high strained forming processes. The main mechanical characteristics of the alloy are summarized in Table 1. All of the measured properties are the mean values of three tests.

Process modeling

In order to investigate the MPIF process, a finite element model was developed using the finite element analysis software Abaqus/Explicit. For each studied case (the pyramidal and the complex geometry parts), the aluminum blank sheet was meshed using linear shell elements (S4R) with five integration points along the thickness direction. A tabulated flow rule coupled to the anisotropic Hill 48 yield criterion is used to define its elasto-plastic behavior. Coarse sized mesh was considered for the area clamped by the blank holders. After a sensitivity analysis balancing CPU time to precision, $2\text{ mm} \times 2\text{ mm}$ shell elements were finally chosen for the rest of the sheet. The forming tool was modeled by an analytic rigid surface. The simulation process was organized into three steps: approach, forming and retraction. During the forming step, the tool controlled by its reference point follows the toolpath trajectory that

Fig. 3 Some of the complex manufactured parts and the corresponding die configurations



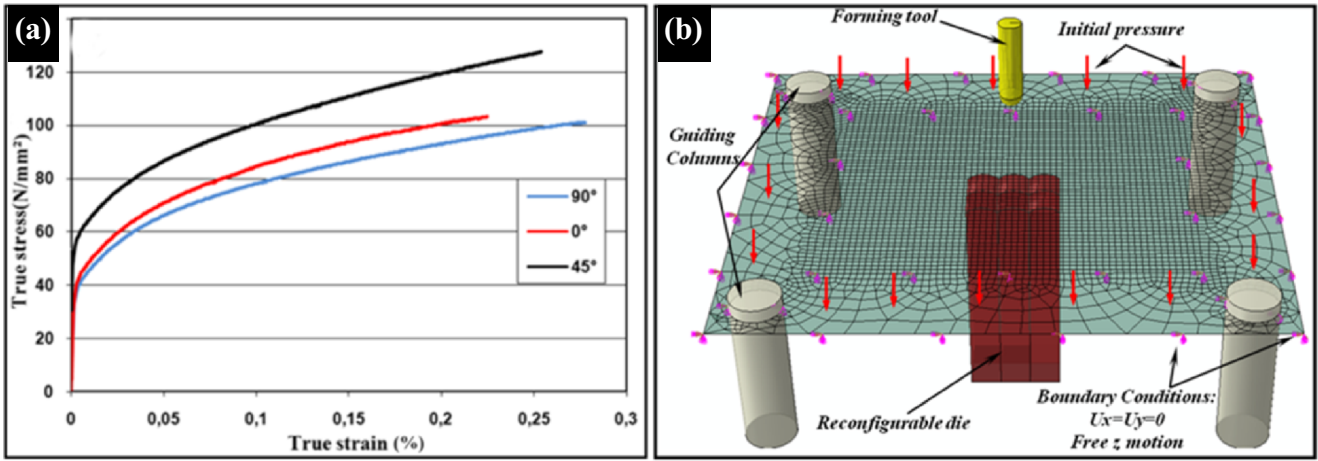


Fig. 4 (a) True stress strain curve (b) Numerical model for the MPIF process

has been already generated by Mastercam. The implementation of this trajectory into the FE software is automatically carried out through an in house developed script using the python programming language (Boudhaouia et al., submitted for publication). Surface to surface contact with hard contact and coulomb friction law were used for the interaction between the forming tool (master surface) and the aluminum deformable sheet (slave surface). A global friction coefficient of $\mu_1 = 0.05$ is chosen for this contact property.

On the other hand, the reconfigurable die and the four guiding columns were modeled as discrete rigid surfaces. The same type of interaction is considered to describe the contact between the sheet and the die but with a friction coefficient $\mu_2 = 0.1$. The imposed numerical boundary conditions, were equivalent to the experiments ones; i.e. only the translation along the z axis has been kept free and an initial pressure (equivalent to the blank holders' weight) was applied on the sheet's periphery. Thanks to this load and the sheet-columns interactions, the sheet's adequate displacement along the z axis was guaranteed. The different instances involved in the numerical model for the pyramidal part forming simulation during the MPIF process are shown in Fig. 4.

Table 1 Mechanical properties of Al 1050A alloy

Density (t/mm^3)		2.7×10^{-9}
Young's modulus (GPa)		69
Poisson's ratio		0.3
Tensile yield strength (MPa)		59
Ultimate Tensile strength (MPa)		115
Elongation at failure A (%)		27
Anisotropy coefficients	r_0	1.79
	r_{45}	2.45
	r_{90}	1.7

Pyramidal part forming

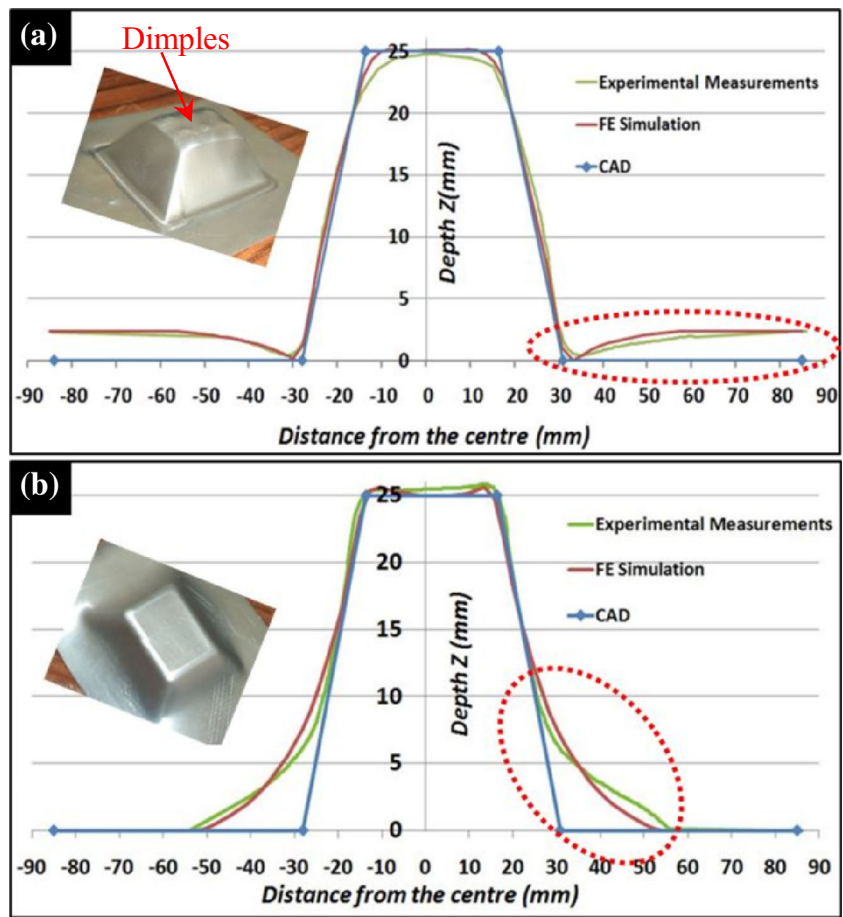
In order to study the influence of the new hybrid process on the thickness distribution and geometrical accuracy, a 25 mm truncated pyramid with a 60° wall angle and a lower $20 \times 30 \text{ mm}^2$ rectangular base is considered. This standard geometry was chosen in order to compare the results of MPIF process to those obtained by conventional ISF. The adequate tool paths of each process were generated by the commercial CAM software Mastercam. The strategy used is offset planes with a vertical increment $\Delta z = 1 \text{ mm}$. For the conventional ISF process, no motion was authorized for the sheet's periphery during the forming experiments and the FE simulation.

Geometrical accuracy

The geometrical accuracy of both the MPIF and conventional ISF processes was estimated by comparing the experimental profiles of the formed parts, along the central cross-section (along the XZ plane), to the numerical ones. The numerical curves were predicted using the finite element model described above and the experimental ones were obtained using a three-dimensional laser scanner. These results, for both manufacturing techniques, were also compared to the initial CAD geometry and the results are presented in Fig. 5.

It can be noted that the numerical and the experimental results are in quite agreement which validates the finite element model proposed in this study. On the other hand, the curves show that for the two studied techniques, the obtained profiles don't exactly match to the desired programmed geometry. However, the overall accuracy of the MPIF formed part is clearly higher than that of the one obtained using the conventional ISF process. For instance, for the first process, the correct wall angle was achieved and maintained for the total depth of the part, unlike the case of ISF where a considerable deviation (Fig. 5b) is observed for the first 10 mm

Fig. 5 Comparison of geometrical accuracy (a) MPIF (b) Conventional ISF



depth. This difference can be explained by a smaller spring back for the MPIF process. As a matter of fact, since the deformation pattern in this hybrid process is quite identical to that observed for the TPIF process, the reduction of spring back in that area could be explained by the uniform distribution of tensile meridional stresses throughout the sheet which comes from the external loading applied by the blank holder. The absence of such loading in the case of the ISF process can result in very localized stress fields which increase the amount of spring back after the loss of contact between the forming tool and the sheet or after the blank unloading [11]. Some deviation, highlighted in Fig. 5a, is also remarked for the MPIF part and more precisely at the periphery of the formed pyramid. In fact, as the programmed toolpath stops at the final depth, the load applied by the forming tool on the sheet is not high enough to cause a further descent of the blank holder and thus only the area around the tool is plastically deformed. An improved result should normally be obtained if the adopted tool path is revised by adding radial supplement contours at the final depth to the original trajectory in order to bring the rest of the sheet to the desired depth and thus reduce the relative disparity compared to the required CAD geometry. Such improvement will be further investigated in future works. On the other hand, the effect of the punches' rounded

ends ('the dimples') is apparent on the pyramidal part obtained by MPIF (Fig. 5a) which could severely constrain, if not eliminated or reduced, the use of this new technique especially for industrial applications. This point will be further analyzed in the case of the complex part forming.

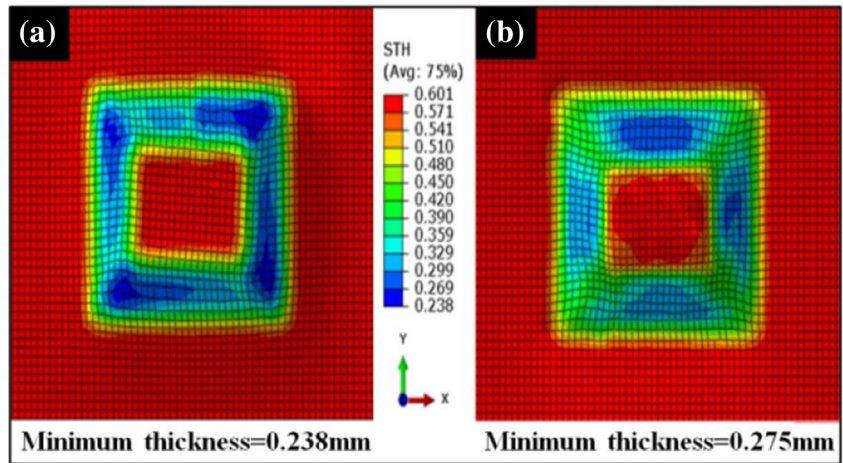
Thickness distribution

Using the finite element model for both processes, we have been able to predict thickness distribution of the formed part. The obtained results are presented in Fig. 6.

As can be seen in this figure, the thickness distribution pattern is quite different for the two formed parts. For the MPIF, the major thickness reduction is observed at the midst of the pyramid walls and especially at the mid height of the part. As for the conventional ISF, all of the central area is affected by a severe thickness reduction exceeding 60% thinning.

To better characterize such thinning phenomena, the evolution of the thickness distribution along two different cutting planes (the diagonal section and the meridian X cross section) was determined and the obtained results are shown in Fig. 7. It has been found that no big difference in the thickness distribution was noted when considering the meridian cross section

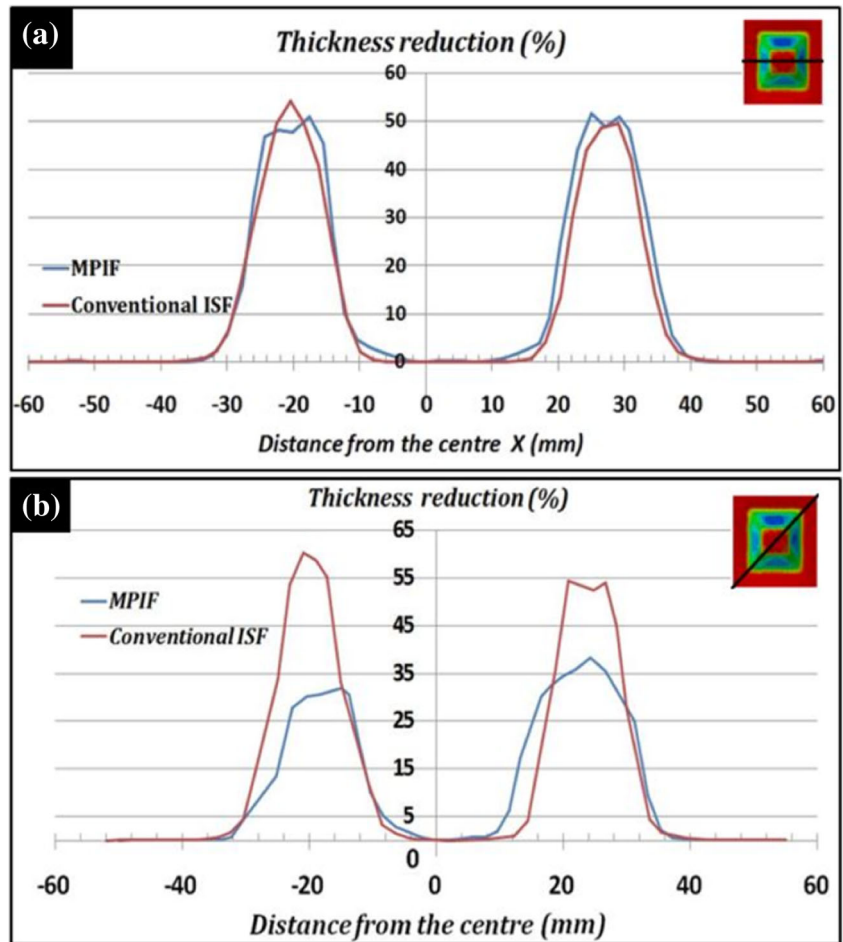
Fig. 6 Thickness distribution for:
 (a) Conventional ISF (b) MPIF



(Fig. 7a) and the two manufactured parts suffer from excessive thinning in that section exceeding 50%. On the other hand, along the second cutting plane, corresponding to the diagonal section, it can be clearly noted that the MPIF process presents a better thickness distribution. In fact, the minimum thickness of the final part along that direction is about 0.371 mm which corresponds to almost 38.2% thickness reduction. For the conventional ISF, the minimum thinning value is 0.2387 mm

which is equal to 60.2% thickness reduction. Therefore, a more homogenous thickness distribution on the whole part and especially on the pyramid faces is noticed for the MPIF process. This improvement is likely due to the presence of the counter-tool (the reconfigurable die's punches). These latter ensure the part stabilization during the forming operation by preventing the floating movement of the sheet which is caused by the forming forces instability.

Fig. 7 Thickness reduction (a)
 Along the meridian X cross
 section (b) Along the diagonal
 section



Moreover, the excessive thickness reduction in the diagonal section could also be linked to the maximum equivalent plastic strain distribution which, in the case of the ISF process, is principally localized at the four diagonal extremities as shown in Fig. 8a. The maximum corresponding equivalent strain value is almost 2.35. However, for the MPIF process, a much more homogenous strain distribution is observed in the whole part and the maximum strain value is noticeably less than that recorded for the ISF process and is equal to 1.86.

Figure 8b shows the Von-Mises stress distribution for the two processes after the forming tool retraction. It can be remarked that the part manufactured using the MPIF technique presents a better and more homogeneous stress distribution compared to the part formed using the conventional ISF which could explain the enhancement of the part geometrical accuracy and thickness distribution for the MPIF technique.

Forming of the part with a complex geometry

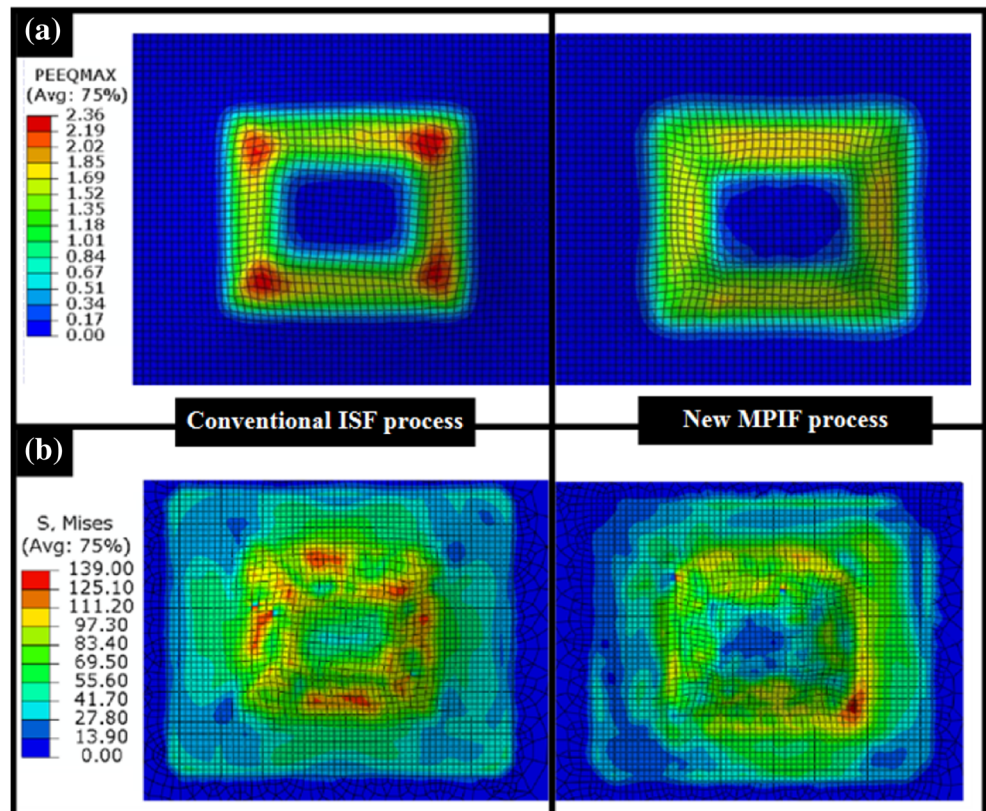
A second part, described in Fig. 9a, was manufactured using the MPIF device. Its intricate geometry was chosen for one main reason which is to highlight once again the flexibility of the hybrid process since, unlike the pyramidal part, this product it impossible to manufacture using the conventional ISF

technique because it contains mixed concave and convex features. The corresponding toolpath, involving a 1 mm vertical increment is described in Fig. 9b. The forming tool starts by forming the concave conical pocket and then moves up and starts the contouring of the square convex region.

Enhancement of the geometrical accuracy

It was concluded from the pyramidal part forming experiment that the overall geometrical accuracy of the parts manufactured using the MPIF process are better than those manufactured by the conventional ISF process. However, the presence of the dimples could limit the efficiency of the proposed technique and its use for industrial parts. As in the conventional multipoint forming process, during the forming phase, the sheet metal is subjected to a concentrated pressure induced by the action of the forming tool associated with the lower punches' ends. It has been shown in many conventional MPF process studies that the use of an elastic piece generally called interpolator improves the contact between the blank and the discrete matrix and thus reduces and even eliminates the dimpling phenomena [4, 16]. This idea was tested in our case and a 2 mm polyurethane interpolator with a Shore hardness of 60 was cut and inserted on the top of the lower reconfigurable die as shown in Fig. 9c. A significant improvement of the final

Fig. 8 Comparison of MPIF and conventional ISF processes (a) Maximum equivalent plastic strain distribution (b) Von-Mises stress distribution



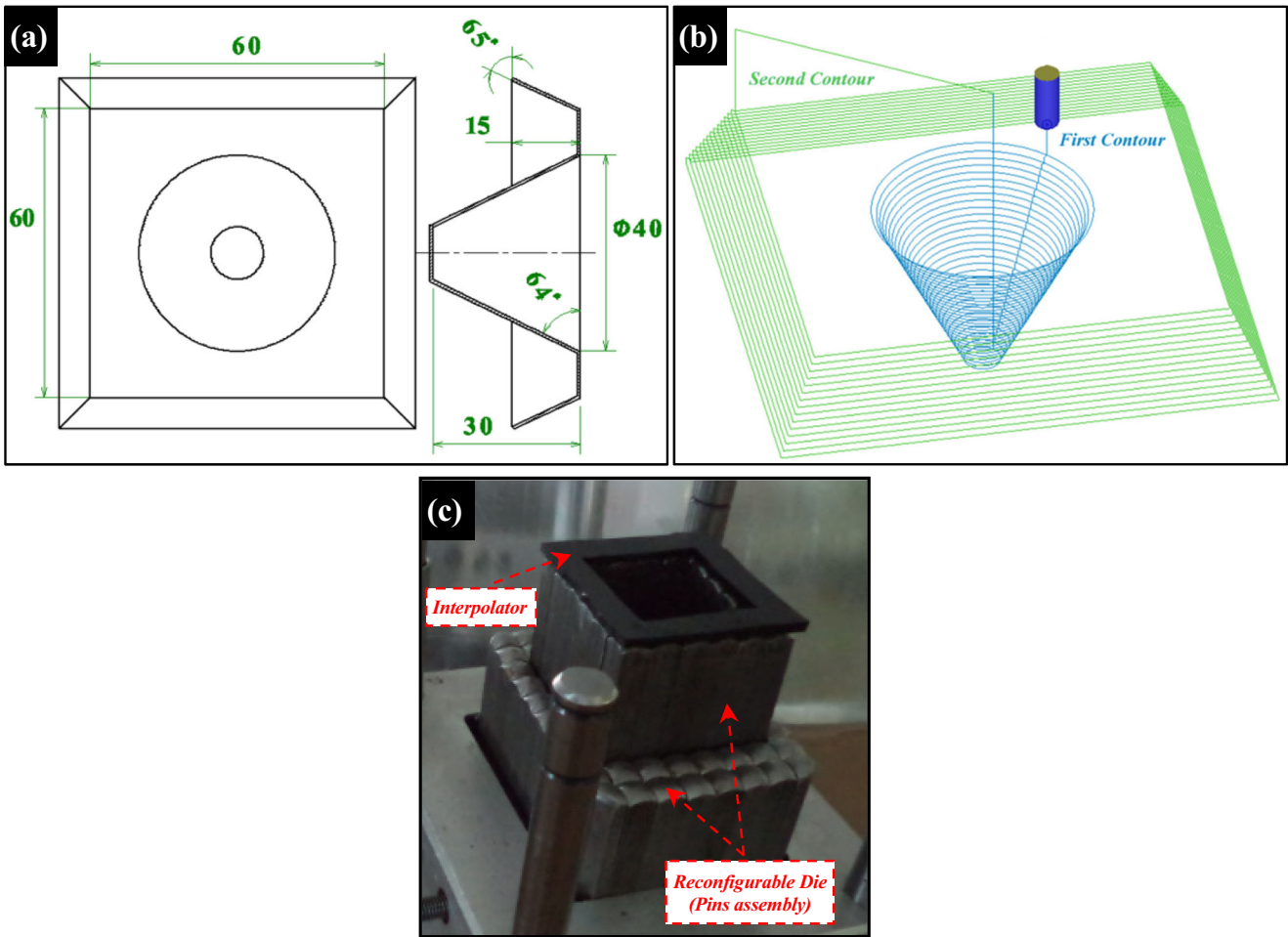


Fig. 9 (a) Description of the manufactured complex part's geometry (b) Corresponding tool path (c) Die configuration with the interpolator insertion

part's quality was noticed: The majority of the dimples are suppressed and homogenous exterior and interior surfaces are obtained for the manufactured part. The improvement of the surface quality can be easily spotted with the use of the interpolator in Fig. 10. On the other hand, a FE analysis is performed to simulate the manufacturing operation including the interpolator. This latter has been meshed using $1.5 \times 1.5 \text{ mm}^2$ bricks with reduce integration. Its behavior has been described by using the Mooney–Rivlin constitutive law, i.e. a rubber like hyper-elastic model. The corresponding material parameters have been identified by means of uniaxial compression tests [16]. Master/slave surface to surface contact algorithms with a friction coefficient of $\mu = 0.1$ were used to describe the reconfigurable die/interpolator and the blank sheet/interpolator interactions.

The obtained numerical results are in good agreement with the experimental ones. As a matter of fact, the reduction of the dimpling defect after the insertion of the interpolator was also obtained using the FE simulation as detailed in Fig. 11a. A more regular surface is observed for the part manufactured using the MPIF process particularly in the upper region originally in contact with the reconfigurable die. In addition, a

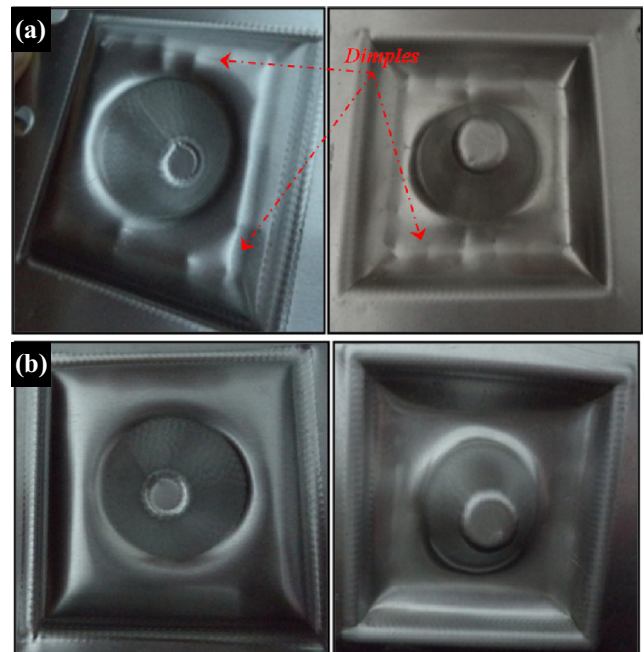


Fig. 10 (a) Part manufactured without an interpolator (b) Same part formed using an interpolator

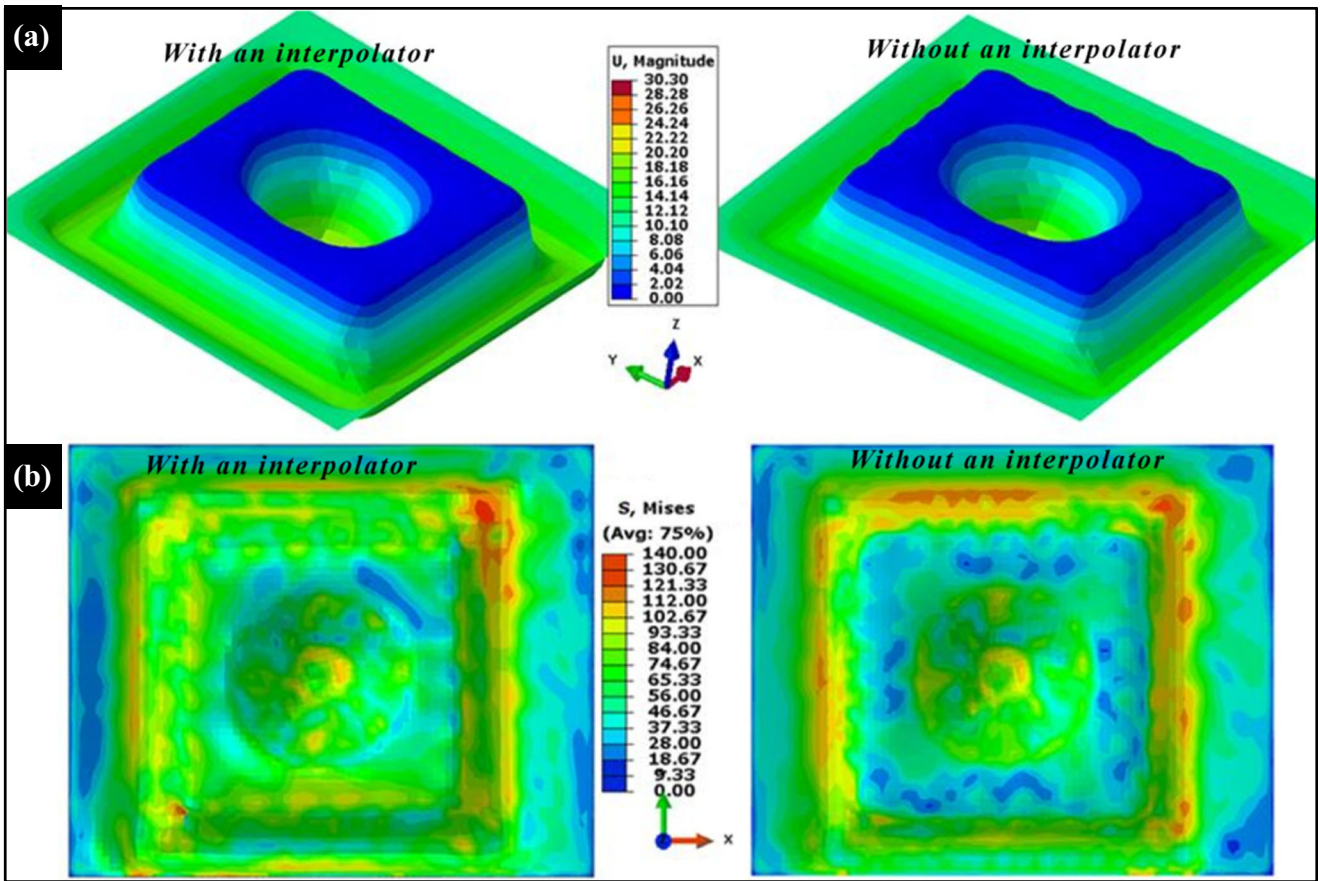
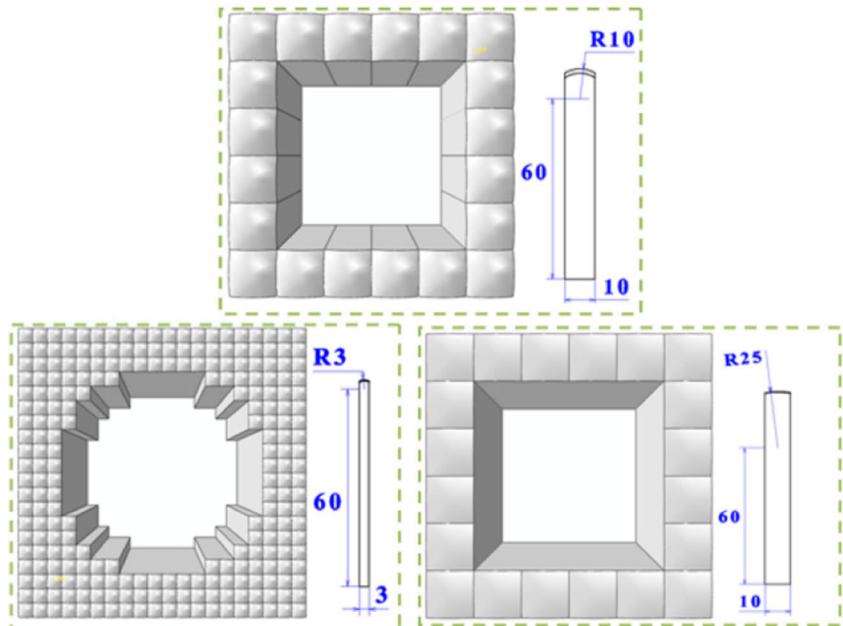


Fig. 11 Numerical simulation results (a) Surface quality evaluation (b) Stress distribution

moderately more uniform stress distribution is obtained when using the interpolator. This could be explained by the fact that in the case no interpolator is used, the blank sheet is locally

stressed as it comes in contact with a discrete and discontinuous surface formed by the pins' ends. When the interpolator is used, the blank sheet is in contact with an almost uniform

Fig. 12 Analysis of the pins' size influence: Dies configuration and pins geometries for the 3 considered cases



surface which is the upper region of the elastic stack. It is worth noting that we think the use of other interpolators with higher thickness or/and hardness will probably result in a better stress distribution and a less pronounced dimpling defects. The influence of the interpolator thickness and properties will be further investigated in future works.

Influence of the rectangular pins size and geometry

In order to analyze the potential effect of the geometry and the size of the reconfigurable die's pins on the geometrical accuracy and the thickness distribution for the manufactured parts,

two additional numerical simulations without the use of an interpolator have been conducted. The same original FE model was adopted and the only change was the modification of the reconfigurable die's geometry accordingly to the change of the pins geometries. The dimensions of the pins for the three considered cases as well as the assembly for each die configuration are presented in Fig. 12. It can be remarked that the die configuration has been kept the same when the $10 \times 10 \text{ mm}^2$ rectangular pins with 25 mm and 10 mm radius tips are used. However, when the size of the pins is reduced to $3 \times 3 \text{ mm}^2$ (with a 3 mm radius end), more pins were added in respect to the geometry of the part to be formed.

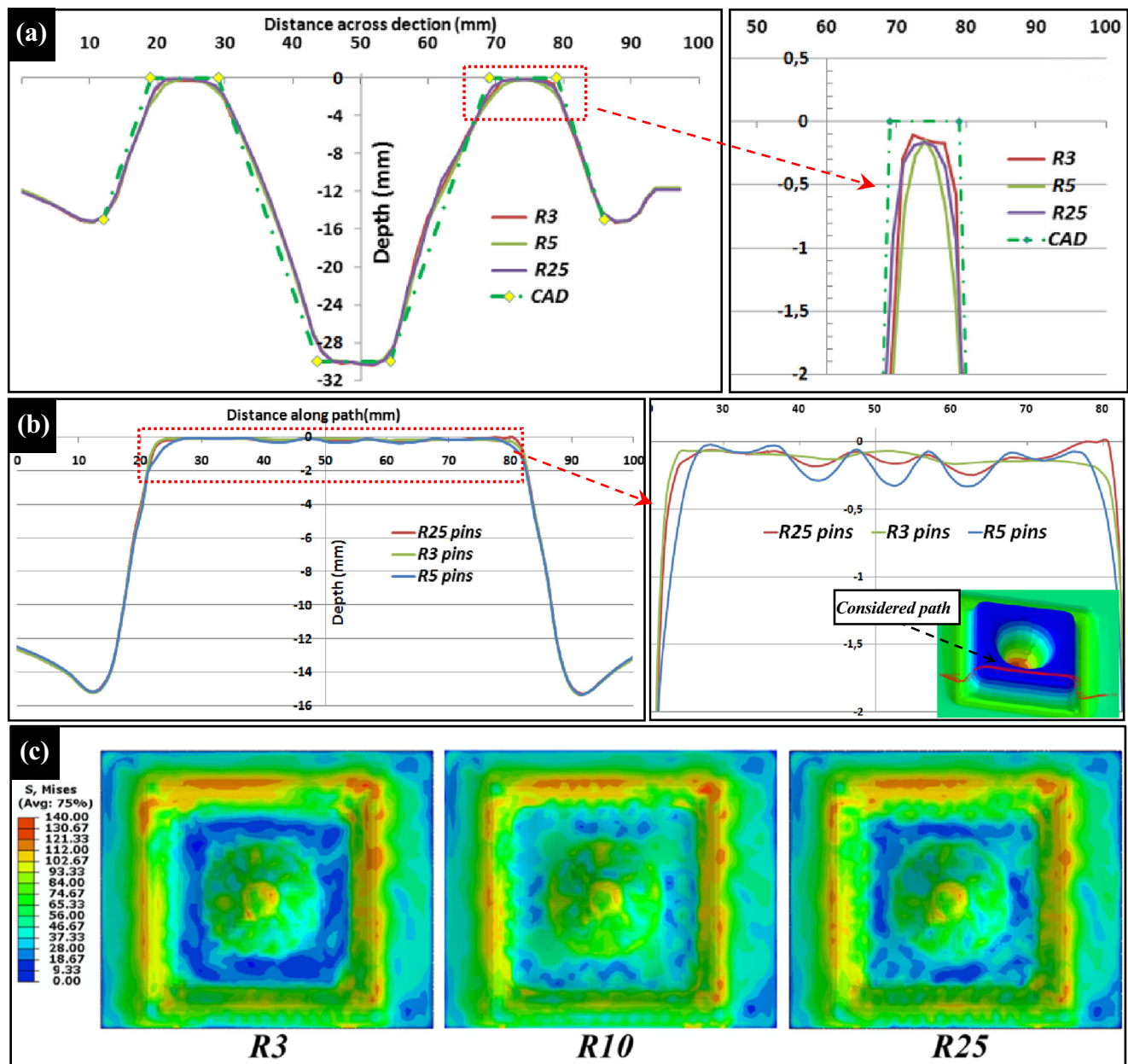


Fig. 13 Assessment of the influence of pins size and geometry on the (a) geometrical accuracy (b) surface quality (c) stress distribution

Figure 13a presents the simulated parts profiles along the middle section (through the center of the MPIF die). As can be remarked, the geometrical accuracy of the different formed parts, in comparison to the desired CAD, is not quite affected by the change of the pins size or geometry. The most affected region is the area in contact with the pins tips. As a result, and taking into account the pyramidal part results, it can be concluded that the geometrical accuracy of the parts manufactured using the MPIF process in relation with the required dimensional specifications is mostly influenced by the upper forming tool trajectory and is not really affected by the pins size or geometry. However, the size of the pins has a great influence on the regularity and smoothness of parts' surfaces: As a matter of fact, as described in Fig. 13b, the best surface quality (the most regular one with the less dimpling effect) is obtained for the 3x3mm² pins. This finding was also remarked in the case of conventional multipoint forming process: In [4], the dimpling effect is significantly reduced and even eliminated when a larger pins density is considered (i.e. when small sized pins are used). However, the reduction of the pins dimensions will complicate the die assembly and the pins adjustment and positioning and also will imply a less economic tooling. Thus, the number of pins must be chosen with care in order to obtain the best forming results but in an economic way. Moreover, the size of the pins' ends has a minor influence on the stress distribution in the part as detailed in Fig. 13c. For the same pins dimensions (10x10mm²) a better stress distribution is remarked for the pins with a 10 mm radius. Consequently, the optimization of the MPIF's parameters (the interpolator thickness, the pins dimensions and geometry, the toolpath strategy, etc.) is strongly recommended in order to ensure the best parts quality. A thorough investigation and optimization of this promising process will be considered in future works.

Conclusions

In this paper, a new hybrid flexible forming process combining the Multi Point Forming and the Incremental Sheet Forming was studied. The results of the finite element model developed to simulate this new technique were in good agreement with the experimental ones. Satisfactory results concerning the manufacturing of several products with standard and complex geometries have been obtained, which demonstrates the feasibility and effectiveness of the developed forming technique. Moreover, a more uniform thickness distribution with a reduced amount of maximum thinning has been achieved for a pyramidal benchmark forming. The part formed using this innovative technique has also exhibited a better geometrical

accuracy compared to the conventional ISF process and it is expected that the difference observed on the part compared to the programmed CAD geometry will be substantially reduced if a proper tool trajectory is considered which will be investigated in future works. On the other hand, the introduction of an elastic interpolator between the blank sheet and the reconfigurable die has led to an enhanced surface quality and a reduction of the dimpling defect caused by the pins' ends. Moreover, this defect was almost eliminated when large pins density is considered or in other words when small pins are used. As a result, a thorough study and optimization of this new technique's parameters (such as the MP die punches geometry and density, the interpolator thickness, type and properties, the toolpath strategy, etc.) is to be considered in future works in order to guarantee a better surface quality as well as an enhanced geometrical accuracy. Moreover, the numerical model will be also developed by introducing an appropriate damage law in order to predict the part's failure.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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