Part precision improvement in Incremental Sheet Forming of not axisymmetric parts using Artificial Cognitive System

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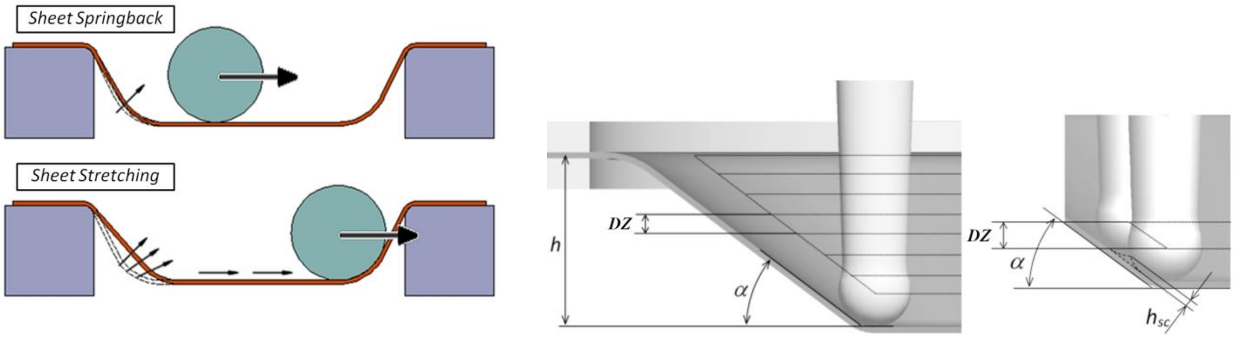
ABSTRACT. Incremental Sheet Forming is a flexible process that uses a hemispherical tool moved by a CNC machine to form a blank sheet. It is adopted in the production of prototypes, small series or customized parts since it is characterized by low costs and long process times. One of its main lacks is represented by the low geometrical accuracy, therefore solutions for errors reduction or compensation are required to improve the process. In this paper, an iterative algorithm based on an artificial cognitive system is presented and validated on a not axisymmetric part adopting different tool paths and materials. The results show that the proposed algorithm allows to achieve a geometrical precision similar to the traditional forming processes.

Keywords: precision, Incremental Sheet Forming, Artificial Cognitive System, Iterative Control System.

1. Introduction

Incremental sheet forming (ISF) is a flexible technology that uses a hemispherical head tool which is moved along a predefined path in order to plastically deform a blank sheet so reproducing the part geometry [Emmens2010]. Usually the blank is held between a backing plate and a blank holder shaped as the outer profile of the part [Micari2007], while a full or partial die can be adopted. ISF is characterized by higher production times with respect to traditional sheet forming technologies, but the use of low cost tools, of standard CNC machines or Robot [Nimbalkar2013] and the low energy consumptions, especially compared to the raw material production [Bagudanch2013], make ISF very flexible and suitable for small batches and single part productions [Jeswiet2005] [Fiorentino2012] [Mitsuishi2013]. Moreover, ISFed parts show a higher formability in terms of achievable wall angles [Filice2002] and Forming Limiting Curves [Jeswiet2005] [Ham2007].

Besides these advantages, the low geometrical accuracy is one of the main drawbacks of ISF [Duflou2007a] and errors exceeding 1 mm are commonly observed [Jeswiet2005] [Fiorentino2011] [Ambrogio2012b]. Errors are due to the sheet springback, stretching and bending [Micari2007] [Jeswiet2005] (Figure 1a), local plasticization due to the punch contact [Guzmán2012], overspinning which results in unwanted bulging [Jeswiet2005] [Duflou2005] or to a low machine stiffness [Meier2009]. Moreover, a curvature called “pillow effect” typically appears on flat surfaces [Micari2007] [Ghamdi2014].



(a) (b)

Figure 1 (a) Springback and stretching action in dieless ISF and (b) constant step depth increment DZ strategy and step depth increment DZ as function of the scallop height h_{sc}.

In order to reduce the geometrical error in ISF and achieve the desired accuracy, many approaches have been proposed. In particular, improvements were obtained acting on the tool path strategy, using a counter die with a consequent reduction of the process flexibility or limiting the scallop effect (h_{sc} in Figure 1b) that, moreover, affects the finishing of the surface in contact with the punch [Attanasio2006] [Attanasio2008] [Fiorentino2011]

Recently some authors suggested a multi pass forming strategy [Liu2014] which consists in several forming stages, each one giving a partial deformation to the part. Multipass forming allows to obtain 90° wall angles [Duflou2008], to form complex parts [Junchao2013] and to improve the accuracy [Bambach2009] [Malhotra2011b]. A similar approach is the backdrawing ISF which consists in working the blank on one side and then on the other so correcting the errors and obtaining more complex geometries [Micari2007][Ambrogio2012a].

Other researches are focused on the development of algorithms for off-line tool path correction that are based on the iterative compensation of the geometrical error. In particular, off-line geometrical measures were used in conjunction with B-spline and morphing techniques [Rauch2009], while an on-line compensation method was developed in [Allwood2009] using the optimal control theory and the characterization of the impulse response of the process. In [Meier2009] Finite Elements (FE) and multi-body-system simulations were used to estimate and compensate the machine deflections in the robot-based ISF. One of the advantages of the off-line forming method is that they can be implemented in a FE environment to simulate the intermediate correction steps and directly produce the corrected part as suggested in [Fu2013].

A different approach is the one based on the correction of the CAD geometry of the part as the one proposed in [Hirt2004]. In particular, in this work the error map is calculated and compensated modifying the original part geometry. The algorithm was tested on an Al99.5 pyramid geometry part and allowed to reach an error range of about ±1mm.

The present research focuses on the CAD correction approach proposing an artificial cognitive system based on the Iterative Learning Control (ILC). The novelty of the research consists in the fact that the part geometry is updated at each iteration and it is further corrected in the next step. Therefore, the correction is calculated at each step by considering the previous iterations too. The algorithm was experimentally applied and calibrated in the case of an Aluminum axisymmetric part [Fiorentino2014a] and preliminary tested on a not axisymmetric Aluminum part using FE simulations [Fiorentino2014b].

In the present paper, the correction algorithm is described and validated considering more general cases. In particular, different materials and tool paths are adopted in the ISF of a part which is characterized by both planar and curvilinear surfaces and different wall angles. Results will show how the proposed algorithm allows to achieve a high part accuracy so making ISF a good alternative to standard sheet forming process for small batch productions.

2. Artificial Cognitive System applied to ISF

The Artificial Cognitive System developed for improving the geometrical accuracy in ISF process is based on an Iterative Learning Control (ILC) algorithm (Figure 2) [Arimoto1984] [Moore1993]. In particular, an ILC consists in the iterative modification of the input $u_k(t)$ of the considered *system* in order to minimize its error $e_k(t)$ defined as the difference between its output $y_k(t)$ with respect to the target $y_d(t)$. As a result, the ILC furnish a new input $u_{k+1}(t)$ for the next iteration step.

The error $e_k(t)$ of the system can be expressed as:

$$e_k(t) = y_k(t) - y_d(t) \tag{1}$$

By choosing a linear first order algorithm for controlling the system, it is only necessary to consider the error of the previous cycle; consequently the new input $u_{k+1}(t)$ can be expressed as:

$$u_{k+1}(t) = T_u(z) \cdot u_k(t) - T_e(z) \cdot e_k(t) \tag{2}$$

where $T_u(z)$ and $T_e(z)$ are linear operators in z that indicates that, in general, their values are variable (i.e. could depend on the error value, the position, …). According to preliminary works that tested the convergence of the algorithm [Fiorentino2014a] [Fiorentino2014b], $T_u(z)$ and $T_e(z)$ are set equal to 1. In such a way the new input $u_{k+1}(t)$ differs from the previous one $u_k(t)$ by an amount equal to the whole error $e_k(t)$.

The positive aspects of this approach are that an ILC learns and controls each cycle. Therefore, a priori knowledge is not required and it can be applied to all the cyclic processes. Moreover, an ILC can be implemented under the hypothesis that the initial conditions of the process are the same at each *k-th* cycle and this can be easily satisfied in ISF since the forming machine, the sheet material and its initial shape are the same for each repetition.

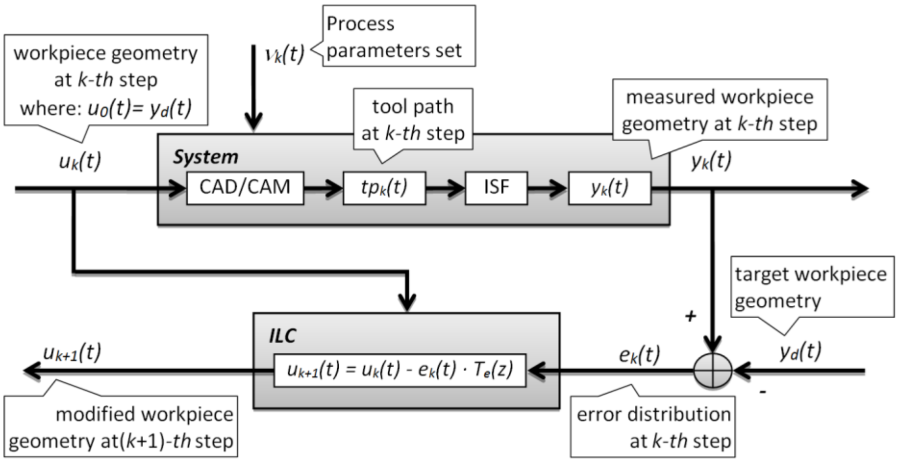


Figure 2 Scheme of the ILC application for improving the part accuracy in ISF.

2.1. ILC implementation in the ISF process

The described ILC algorithm was applied to improve the geometrical accuracy of ISFed part (Figure 2) considering as *System* the whole ISF manufacturing process from the toolpath $tp_k(t)$ definition to the final part measurement. In particular, the idea it to achieve the desired accuracy compensating the error directly on the part geometry . Therefore, the input of the system at the *k-th* step is the part CAD geometry $u_k(t)$ which is iteratively corrected by the ILC. The output is the final part geometry $y_k(t)$ that is compared with the desired part geometry $y_d(t)$ in order to estimate the geometrical error map $e_k(t)$ according to (1). The ILC is the compensation algorithm that, according to (2), calculates the new part geometry $u_{k+1}(t)$ for the next step from which a new toolpath is derived (tp_{k+1}). This is repeated till the error $e_k(t)$ falls within a desired range. Moreover, when the algorithm starts, $u_0(t)$ coincides with $y_d(t)$, the process parameters $v_k(t)$ (i.e. toolpath strategy, tool feed or lubricant) are set and then kept constant during the iterations.

According to this procedure, the precision of the formed part increases at each step until the geometrical tolerance requirements are accomplished (Figure 3a).

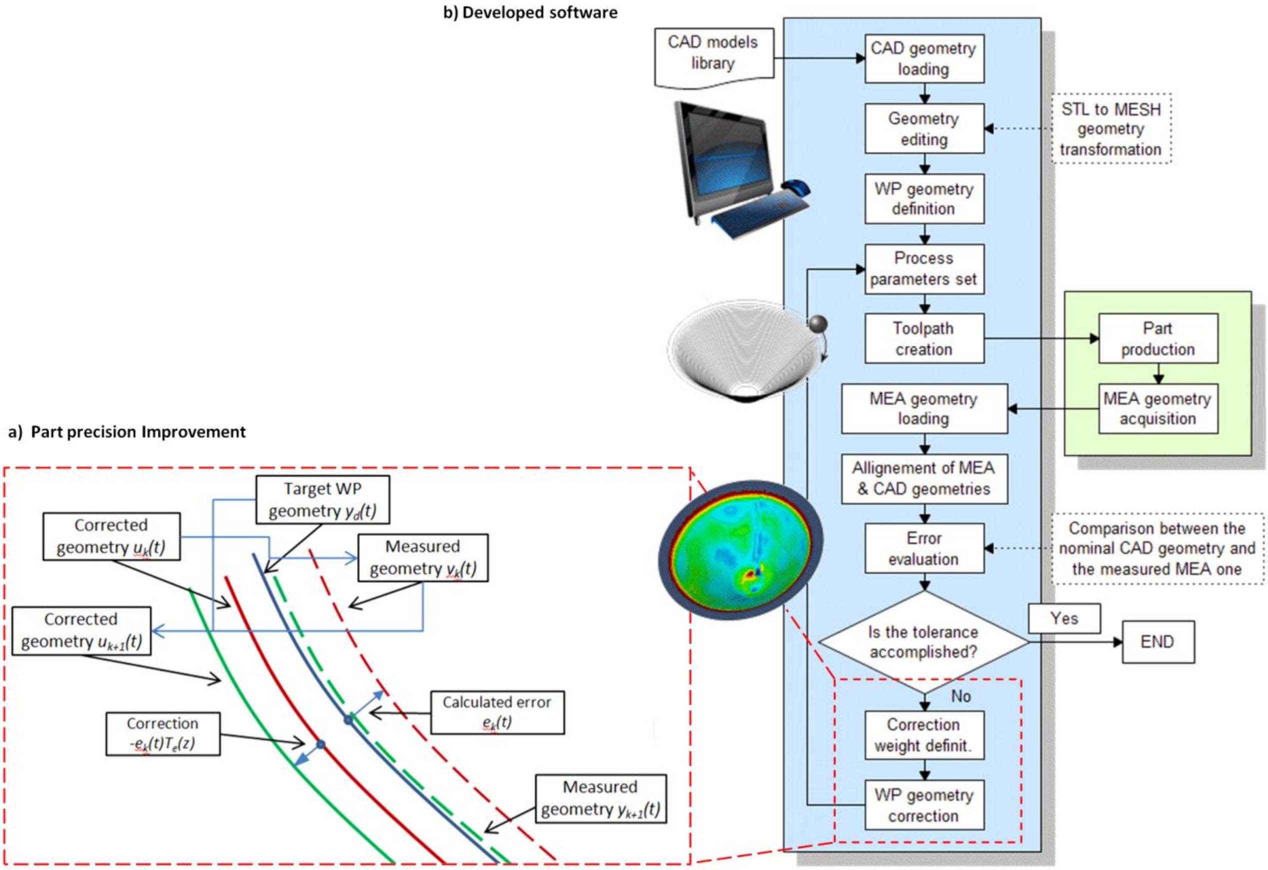


Figure 3 (a) Representation of the effect of the ILC applied to the part geometry correction in ISF and (b) the scheme of the developed software.

All the calculus phases were implemented in a self-developed software (Figure 3b) able to process all the data at each step. In particular, this allowed the complete control of the toolpath $tp_k(t)$ definition in the CAD/CAM module. This ensure that the tool trajectory does not significantly change within the iterations and that the punch stretching effect on the sheet is globally kept the same. In this way, the error is locally compensated without affecting the geometry of farther areas. Moreover, the measured geometry $y_k(t)$ is obtained from an 3D scan of the part (MEA geometry acquisition in Figure 3b) which gives a different CAD definition of the geometry with respect to the target one $y_d(t)$. Therefore, specific modules of the software were required for geometries alignment, nodes projection for the error map $e_k(t)$ estimation and compensation node by node. In particular, the alignment is performed minimizing the RMS of the errors $e_k(t)$. In this way, the precision of the formed part is step by step improved according to the definition of the form tolerance for any surface (ISO 1101-2012).

In order to compensate the elastic recovery after unclamping, the part is measured after it is removed from the machine. Moreover, the comparison between the part and the target geometries is performed considering the sheet surface that is not in contact with the punch during forming. Finally, an optical 3D scanner (RevEng LE 240 HD 1.3 MPx) was used so to speed-up the geometry acquisition time

Further details on the optical 3D scan and on the software are reported in [Fiorentino2014b].

3. Experimental validation

The algorithm for error compensation based on ILC was experimentally tested on a not axisymmetric part using different blank materials and toolpaths. Moreover, a new specimen was used for each iteration step so to be able to compensate the areas that needed to be lowerformed rather than overformed only.

The results of the tests were compared in terms of geometrical accuracy that was achieved on the final part.

3.1. *Case studies*

The geometry considered in the experiments is reported in Figure 4. It was designed in order to reproduce a general ISF process characterized by many features that require tool movements that are parallel, orthogonal and transversal with respect to the sheet rolling direction. Moreover, both planar and curvilinear surfaces having different wall angles (0°, 29° and 38°) are formed. The component overall dimensions are 150x150mm (excluding flanges) with a 30mm depth. In particular, the correction algorithm was applied to the areas that are not in contact with the backing plate during forming so to be able to compensate the error in both directions and to not change the conditions at the boundary of the blank (Figure 4).

Aluminum and steel alloys were considered for the tests and a constant Z tool path strategy was adopted. In particular, Al 1050A and DC04 1mm thick sheets were formed using a step depth DZ equal to 0.1 and 0.3mm. The tests were conducted on a CNC milling machine (Figure 5) using a Rs = 7mm spherical head tool, a feed f = 1m/min, grease as lubricant, a backing plate and a blank holder having the same outer profile of the part.

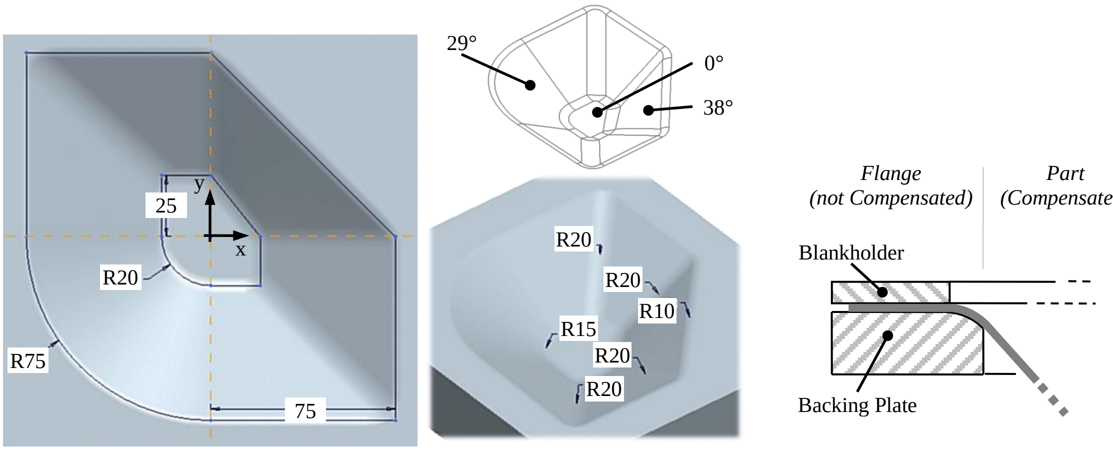


Figure 4 Part geometry used in the case studies for testing the compensation algorithm.

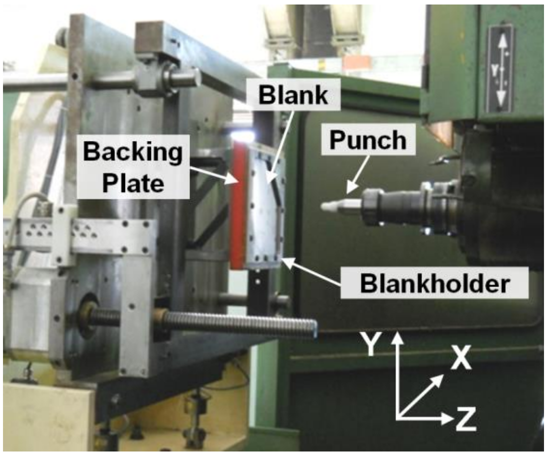


Figure 5 Experimental device setup.

3.2. *Results and discussion*

The results are presented and discussed in terms of the obtained geometrical accuracy correlated to the part geometry, the adopted material and toolpath and the improvements achieved using the correction algorithm. In particular, Figure 6 to Figure 9 report the topographic map of the geometrical error and its frequency distributions for Al 1050A and DC04 alloys at the end of each iteration of the compensation algorithm. The error distributions are compared in terms of average value and uniformity. In particular, the value corresponding to the peak of the error frequency distributions was used to estimate the average error (Figure 10 and Figure 11) while the frequency slope (Figure 6 to Figure 9), its scattering (Figure 10 and Figure 11) and width (Figure 12) were used to evaluate the error uniformity. The scattering was estimated as the range that contains the 99.7% of the samples while the width was measured at 1/5 of the peak height.

Error distribution on the part geometry

The geometrical error that is obtained for the part geometry in Figure 4 when formed through the ISF process is shown in Figure 6 to Figure 9 at the step k = 0.

The figures show that the error map is generally not symmetric and depends on the local features of the part. In particular, the most critical ones are the boundary and the bottom (0° flat surface in Figure 4). In fact, the zones on boundary are the farthest from the punch and the closest to the backing plate and, therefore, they are subjected to more severe bending stresses during forming. Since bending stress are one of the causes of geometrical inaccuracy, these areas are affected by a high error. Whereas, the errors present on the bottom of the part are due to the pillow effect [Micari2007]. The other areas of the part are affected by a lower error which is particularly located on the highest angle surface (38°) and on the transitions between the features of part.

Effects of the material and the tool path

The samples obtained using different materials and toolpaths show differences in the error map as reported in Figure 6 to Figure 9 at the initial step (k = 0). In particular, it can be observed that the use of DC04 alloy increases the error with respect to the Al 1050A alloy. This is in accordance with the properties of the two materials where the higher elastic module of the steel alloy leads to a higher springback. Moreover, the error is lower when high values of the stepdepth are used (DZ = 0.3mm). This could be reconducted to an overspinning of the material [Jeswiet2005] [Duflou2005] that occurs when closer punch passes (DZ = 0.1mm) are adopted.

Achievements of the correction algorithm

In order to compensate the previously described errors and to obtain a part characterized by closer geometrical tolerances, the error compensation algorithm was applied to the tested cases.

The slope of the error frequencies distributions in Figure 6 to Figure 9 show that at each step the geometrical error becomes more uniform and similar to a Gaussian distribution with a slight asymmetry. This allows to use the error value of the distribution peak as representative of the average error value that is achieved.

In all the tested cases, the results show that after the first correction (k = 1) the average error (Figure 10 and Figure 11a) and its uniformity have a significant reduction in terms of both scattering (Figure 10 and Figure 11b) and width (Figure 12), while after the second correction (k = 2) the first gets almost stable while the uniformity is further improved. In particular, within few steps the average errors reach a stable value of 0.1mm (Figure 10) being reduced of about 50% (Figure 11a), while the error scattering (Figure 10, Figure 11b and Figure 12) is reduced of about 40% from [-0.62; 0.63] to [-0.40; 0.34] when forming Al 1050A and from [-0.91; 0.62] to [-0.55; 0.39] for DC04 steel. Moreover, the total reduction of the error scattering is affected by the toolpath (Figure 11b and Figure 12). In fact, for both materials the total error scattering is reduced by 45% when using DZ = 0.1mm, while it is reduced by 36% when DZ = 0.3mm. This can be explained by the fact that for each material the achieved error scattering (K = 2) is almost the same while in the case of DZ = 0.1mm it is initially higher (K = 0).

Overall outcome

The previous discussion shows that the chosen part geometry, materials and toolpaths allowed to reproduce many of the causes of inaccuracy in ISF so obtaining a complex error map on the part. Thanks to the use of the correction algorithm that is presented in the present paper, the errors were well compensated so achieving a good geometrical accuracy for all the considered part features and in the transition zones between them. In particular, the algorithm allowed to significantly improve the geometrical accuracy of a not axisymmetric part in terms of average error, scattering and uniformity independently from the worked material or the adopted tool path. As a result, tolerances of about ±0.5mm were achieved so obtaining a geometrical accuracy that is comparable with the ones obtainable in traditional sheet forming process as drawing. Moreover, the final accuracy resulted to depend from the chosen material but not from the stepdepth. Therefore, the use of the method allows to chose a proper stepdepth value according to other manufacturing constrains as the part finishing or process time.

Finally, the monotone reduction of the geometrical error validated both the convergence of the method and the values that were chosen for the linear operators in equation (2) ($T_u(z)$ and $T_e(z)$ equal to 1).

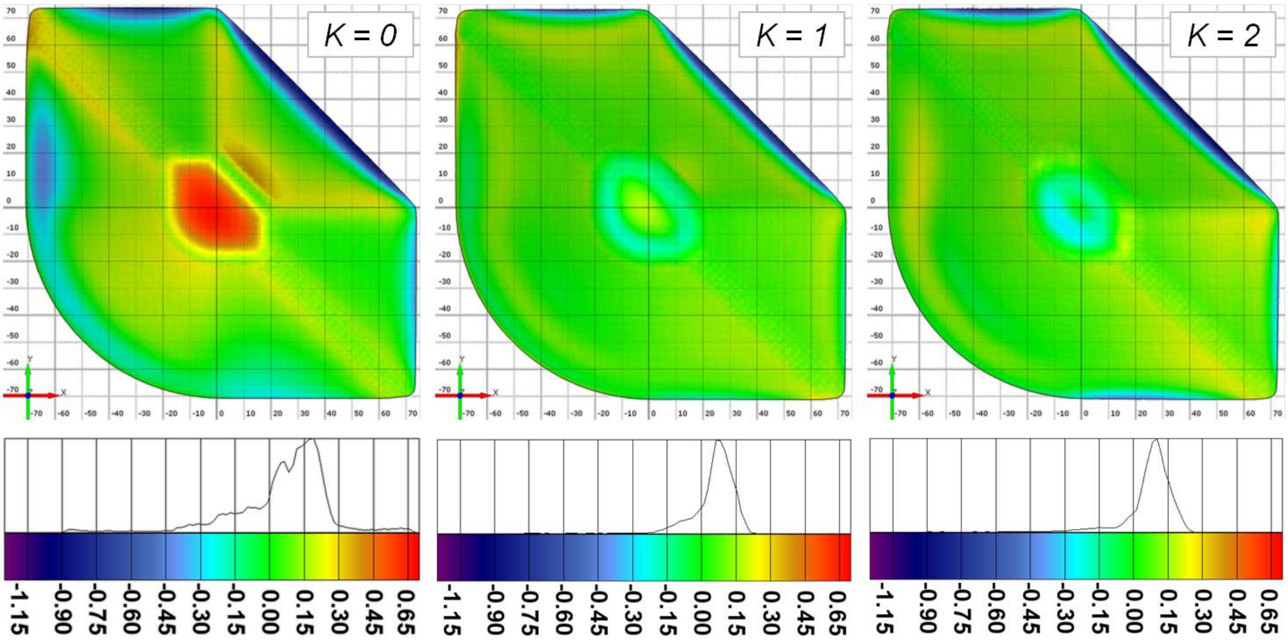


Figure 6 Geometrical error maps and frequencies obtained at each step of the correction algorithm (Al 1050A DZ= 0.1mm).

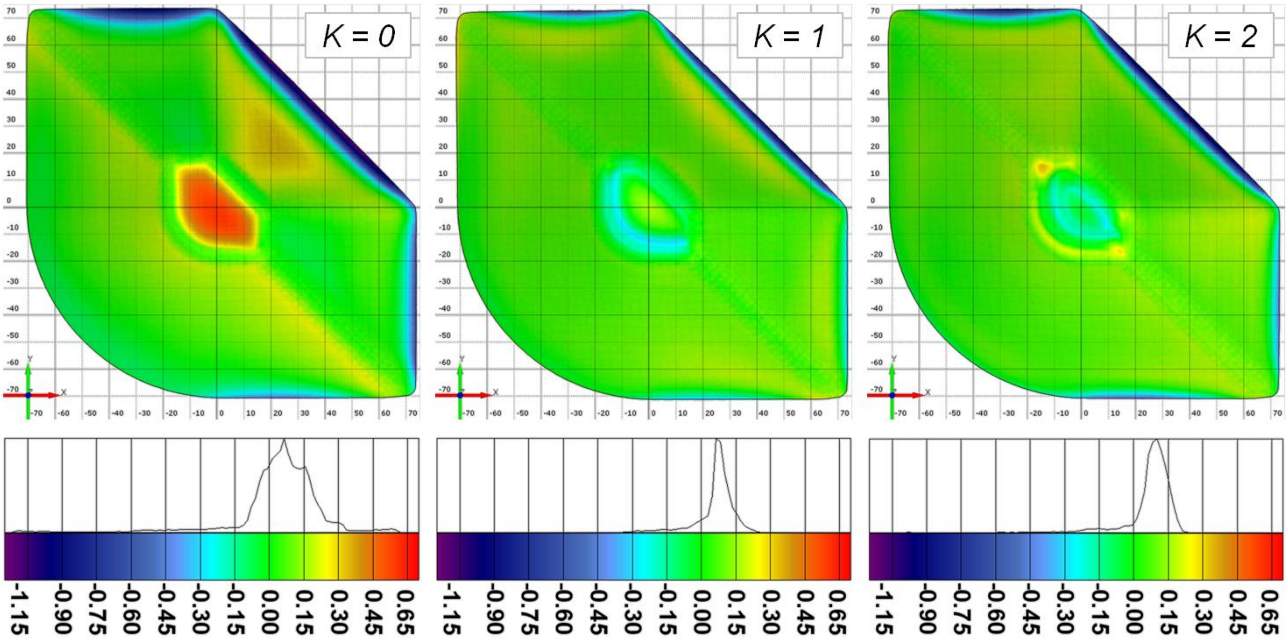


Figure 7 Geometrical error maps and frequencies obtained at each step of the correction algorithm (Al 1050A DZ= 0.3mm).

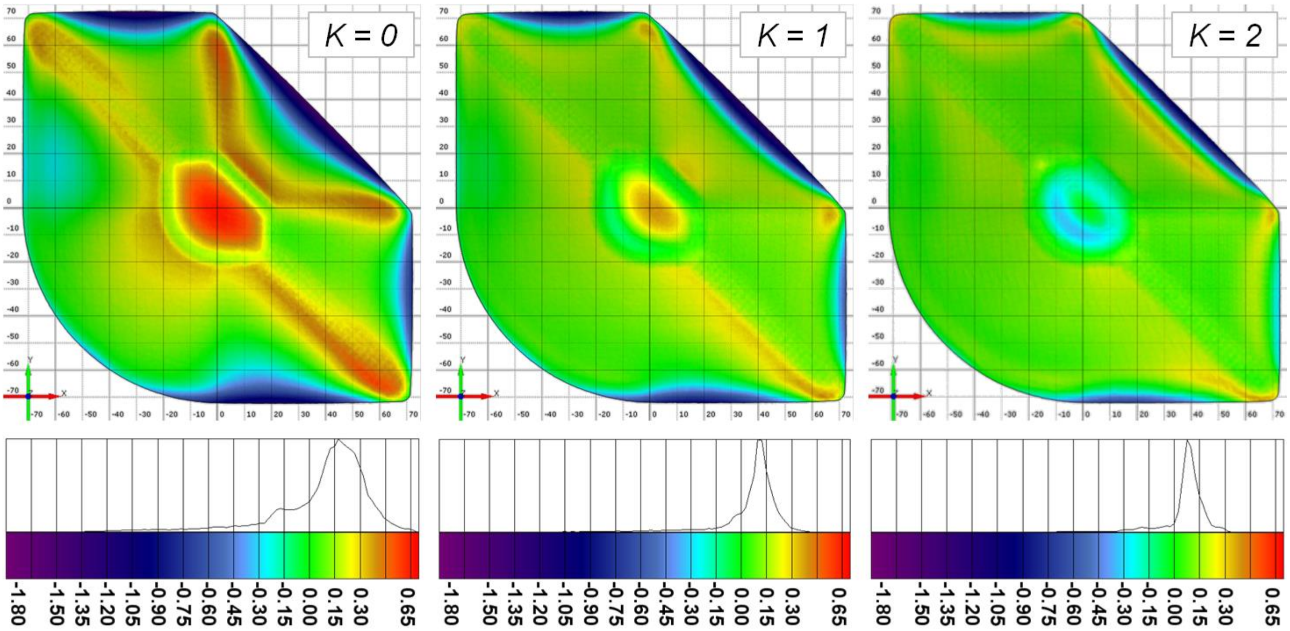


Figure 8 Geometrical error maps and frequencies obtained at each step of the correction algorithm (DC04 DZ= 0.1mm).

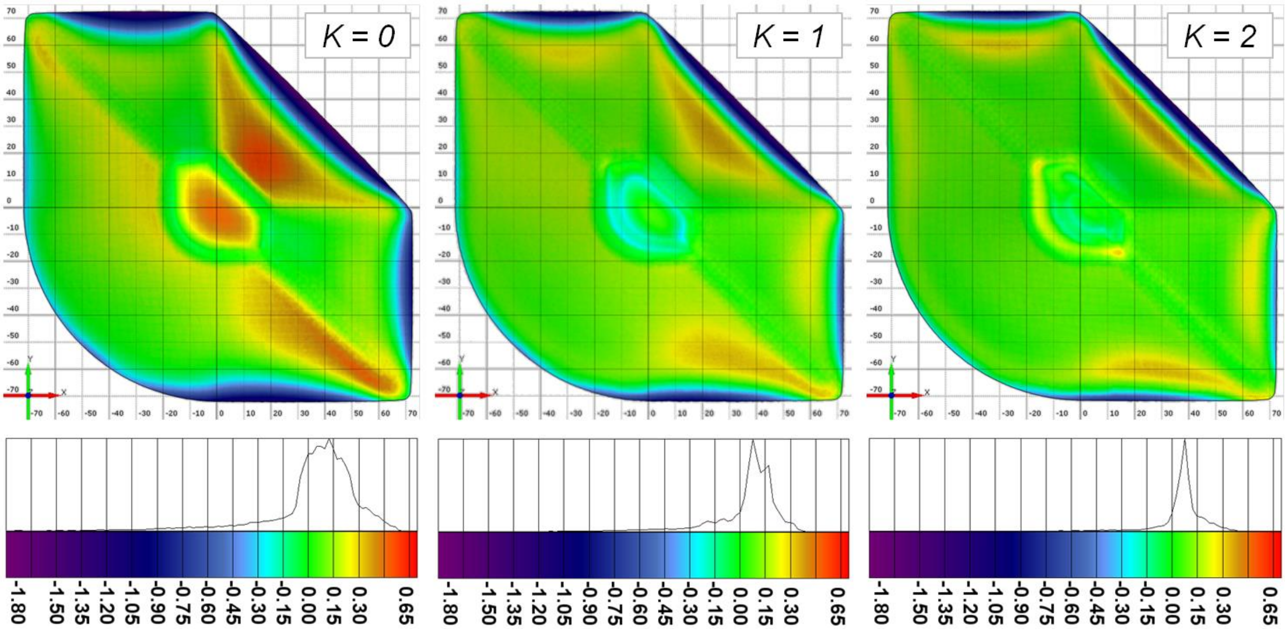


Figure 9 Geometrical error maps and frequencies obtained at each step of the correction algorithm (DC04 DZ= 0.3mm).

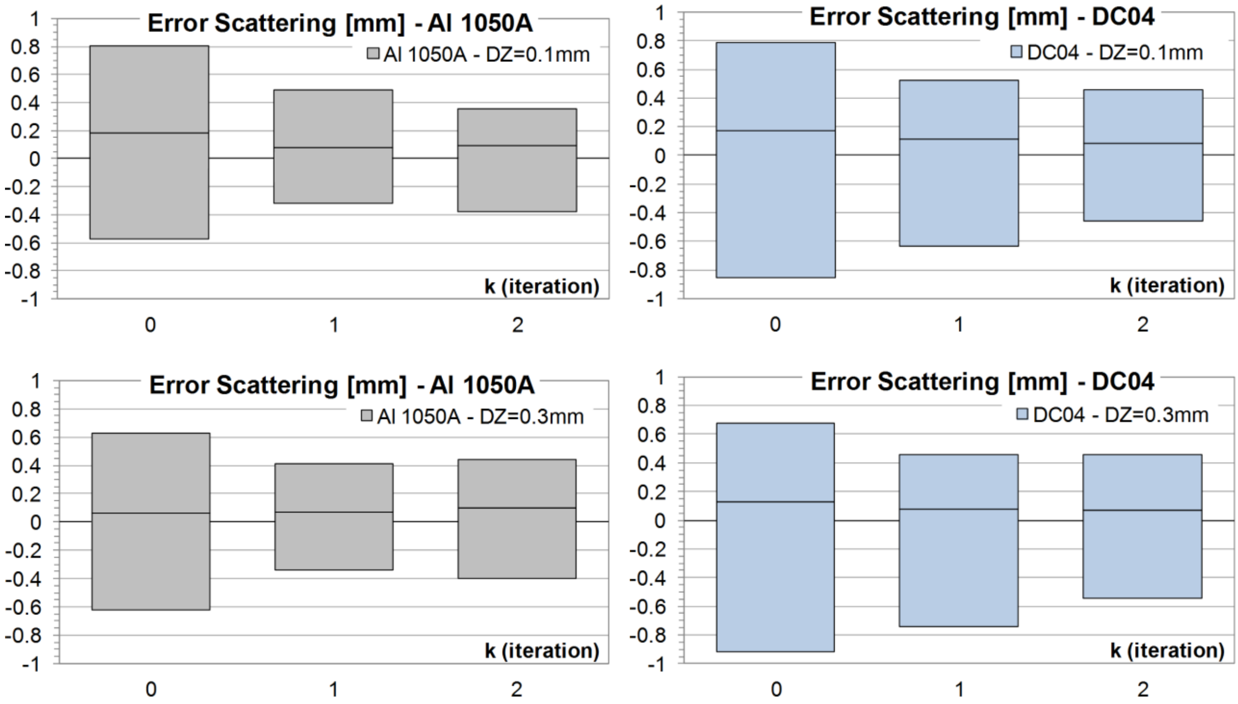


Figure 10 Average error (peak position) and scattering (99.7% of the data) of the error frequency distributions at the end of the correction algorithm steps.

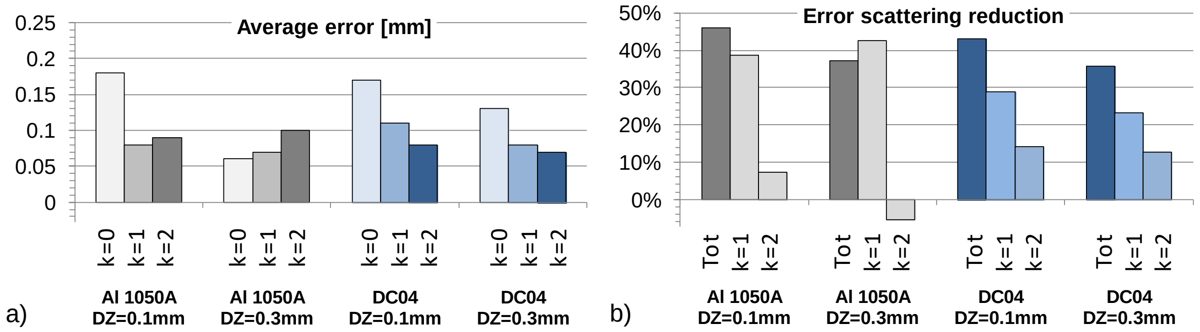


Figure 11 Comparison of the geometrical error at the end of the correction step. a) average and b) scattering values (peak position and 99.7% of the data).

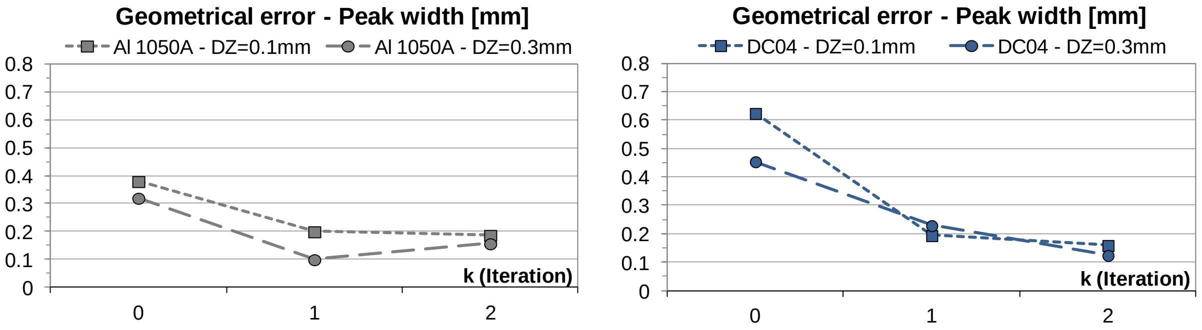


Figure 12 Width of the frequency distributions measured at 1/5 of the height of its peak at the end of the correction algorithm steps.

4. Conclusions and future works

Incremental sheet forming is a flexible technique economically suitable for low volumes or single part productions. One of the main drawbacks of the process is the low geometrical accuracy achievable on the workpiece due to phenomena like springback, sheet bending or stretching.

In order to improve the process, a general method for error compensation was developed, implemented in a self-developed software and tested on a simple geometry. It consists in an Artificial Cognitive System based on Iterative Learning Control that iteratively compensates the geometrical error based on the CAD model of the part till the desired dimensional accuracy is achieved.

This paper aimed at testing the capability of the algorithm in a more general case. In particular, it was tested on a not axisymmetric part characterized by planar and conical surfaces having different inclinations. Results showed that the chosen part geometry is representative for the main causes of inaccuracy in ISF. Moreover, they showed that the method is able to achieve tight tolerances on the whole part so making ISF a good alternative to traditional sheet forming technologies when the geometrical accuracy is considered. Moreover, the method uses an optical scanner, it requires standard computational resources and no communication with the forming machine is need. Therefore it is versatile, its implementation does not require high or dedicated investments and it results to be a fast method that allows to acquire the 3D part geometry and to compute all the calculus within few minutes. Moreover, since no intermediate test dies (or final ones) have to be manufactured, the lead time of the product is reduced from months to days.

By analyzing the capability of the method, it was observed that further improvements can be achieved. In particular, local compensation strategies will be implemented in the areas close to the backing plate and the flat ones where higher bending and pillow effect phenomena respectively occur. Moreover, since the most critical zones to form resulted to be the ones where severe deformations or springback occur, further research will be focused on testing more critical cases as when higher stepdepths are adopted or difficult to form alloys, as titanium, are worked. In addition, a further increase of the global efficiency of the ISF process will be obtained integrating the algorithm with FEM results in order to afore compensate the error and to directly manufacture the corrected part at the last iteration.

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