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ORIGINAL ARTICLE

Improving industrial suitability of incremental sheet forming process

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Abstract Although in the last years a large amount of research work has been spent on incremental sheet forming process, industrial applications are not spreading accordingly. This is due to process characteristics such as slowness and limited accuracy. In the paper, the authors investigated the suitability of incremental sheet forming at very high feed rates to strongly reduce processing time. What is more, a simple strategy to reduce the part inaccuracy was implemented. The investigation concerned a simple conical shape but the obtained results are quite general.

Keywords Incremental sheet forming · High speed · Accuracy

1 Introduction

The request of flexibility in manufacturing by the market actors pushes the researchers' interest towards the development of new processes which allow the products differentiation, being the latter a key success factor in manufacturing practice [1]. In turn, the large investments of the metal stamping processes—due for instance to die set costs—require large-scale productions to generate a suitable payback.

In this scenario, the development of flexible technologies assumes a relevant role: Nakajima introduced about 40 years ago the so-called multi-point forming technology, an automatically reconfigurable discrete die that used a positioning stylus mounted to the headstock of a numerical control milling machine to position the matrix of round pins [2]. By 1996, many famous scientists started to study a kind of soft tool technology; the most famous today is the hydroforming, which adopt oil, water, or other fluid mediums as the punch or the die as well detailed in [3]. In 2000, Ahmetoglu and Altan collected a large review on the fundamentals of the tube hydroforming; in particular, they analyzed the relationship between the achievable part geometry and the process variables such as preform geometry, lubrication, and so on [4]. More recently, the laser forming technology was introduced to the scientific community, a laser is used to scan a blank with a certain pattern so that the material deforms owing to the thermal-induced distortion [5, 6]. Further technological alternatives could still be derived from the literature. Anyway, looking at the technical and scientific literature, it is easy to observe that many new techniques do not leave the research laboratories, playing a marginal role in the added value creation. Incremental sheet forming belongs to the above processes cluster since, although its high potentialities, today it is a topic for scientists rather than an alternative solution for industries [7, 8]. Actually, two of the main reasons why incremental forming is not applied on a larger scale are related to two strong drawbacks that penalize the production, namely the process slowness and the part accuracy [9, 10]. In incremental sheet forming, the process time is usually estimated in tenths of minutes and this deeply impacts on the global productivity. What is more,

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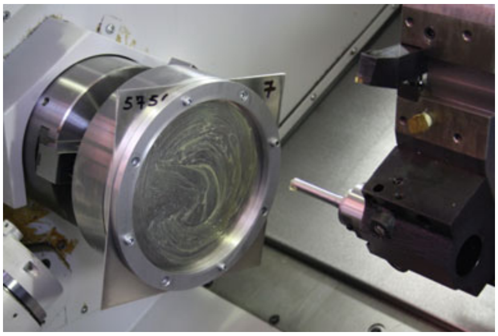


Fig. 1 The equipment used

the discrepancy between computer-aided design (CAD) geometry and the actual one can be of the order of millimeters and this also limits any subsequent assembling process. These considerations, in the opinion of the authors, are the main reasons why incremental sheet forming today is successfully applied only in prototyping steps or in the manufacturing of very small batches [11].

The present investigation tries to modify the above point of view introducing the idea of high-speed incremental sheet forming already indicated in [12]. More in detail, in the paper, the feasibility of incremental forming at very large values of the tool feed rates—definitively larger than in [12]—is investigated highlighting consequences in terms of material response and process issues. Furthermore, in order to improve the process accuracy, the forming step was repeated on both the sides (backdrawing incremental forming) [13]. This latter issue was effective since the time consumption, at high tool feed rates conditions, is not prohibitive. The obtained results were surprising and the main interesting aspects are discussed in the next sessions.

2 The experimental tests

The idea of the research is focused on the possibility to deform the blank with a very high strain rate; for this reason, the experimental campaign was performed on a computer numerical control (CNC) lathe, which allows to work up to 2,400 m/min using the developed tooling.

A dedicated clamping equipment was used as shown in Fig. 1 and square blanks (240×240 mm) were mounted between two circular rings, obtaining a 200 mm diameter circular working zone. The rings were bolt together in order to allow the sheet rotation on the fixture in the backdrawing step. The hemispherical punch was fixed to the machine holder by means of a holder and a bearing to allow its free rotation according to the process conditions; grease was used to reduce friction between punch and sheet. Since a CNC lathe was used, an axisymmetric shape was considered, namely a frustum of cone having a major base of 180 mm and a final depth of 50 mm. Three aluminum alloys, AA1050-O, AA6082-T6, and AA5754 were taken into account in different thicknesses. The three alloys were chosen according to their diffusion in technical literature and industrial applications; in detail, AA1050 is usually considered as a benchmark material, AA6082 is the most utilized structural aluminum alloy, and AA5754 is a trade-off between strength and cost.

Part revealing was one of the critical tasks of the study. To obtain the geometry of the real part, a reverse engineering approach was implemented and a laser-based scanning system was utilized to pursue the above goal. Figure 2 shows the result of a particular test and the relative virtual model, obtained by the laser scanning.

The different surfaces, which reproduce the CAD geometry and the virtually obtained one, were managed utilizing RapidForm™ 2006 and compared applying a proper procedure. The latter, permitted to minimize the positioning error between them, also using a few markers, traced on the measured surface. In this way, it was possible to reproduce the discrepancy map between two surfaces, such as the one displayed in Fig. 3.

Starting by this "overlapping", the utilized software is able to automatically calculate the average error (E_{ave}) by the equation:

$$E_{ave\_j} = \frac{1}{N}\sum_{i=1}^{N}\left|z_i - z_i^*\right| \qquad (1)$$

where, N the number of measured points, z_j^* the expected value, and z_j the measured one.

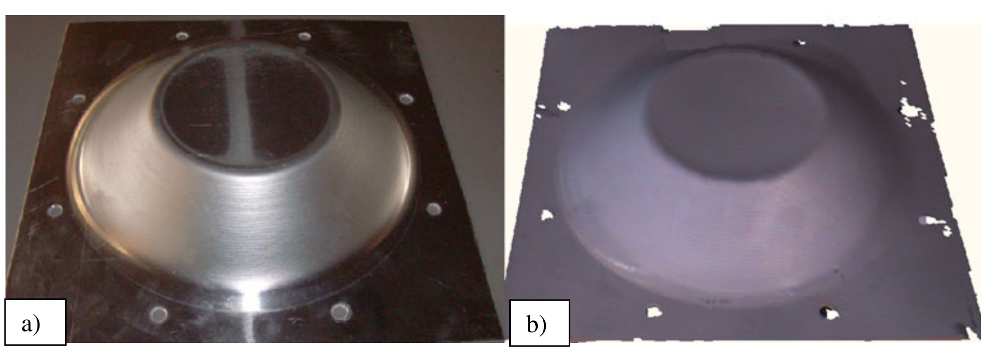


Fig. 2 **a** A realized part and **b** its virtual model

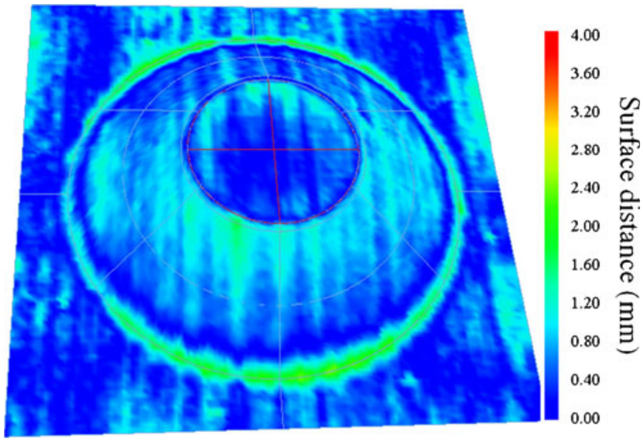


Fig. 3 A discrepancy map between CAD and virtual model

3 The plan of experiments

It is widely recognized that the statistical techniques can be a powerful aid in designing new products and systems, improving the existing ones, and developing and improving the production processes [14, 15]. Furthermore, when several factors are of interest in an experiment, a factorial experimental design should be used; typically a 2^k design represents the most efficient solution. Anyway, in case of "time consuming" experimentations, like the one considered in the present study, a fractional factorial design 2^{k-1} can be adopted [15]. The latter provides the smallest number of runs for which k factors can be studied in a reduced number of experiments. It should be observed that, due to the introduced simplification, the obtained response function is approximately linear over the range of the chosen factor levels.

As the present study is concerned, five factors were considered, namely the sheet thickness, the tool punch diameter, the tool pitch (p), the wall inclination angle (α) and, of course, the tool feed rate (V). A schematic diagram of the investigated factors is displayed in Fig. 4; the investigated ranges, instead, are summarized in Table 1.

In particular, the formability limit for each material and the relative maximum critical slope angle (α_{max}) being known, the investigation was executed in safe conditions, fixing the lower and upper bounds of the range respectively at the 60% and 90% of the α_{max}.

As concern the tool speed, it is interesting to note that a set of FE simulations were preliminary executed, highlighting that the material strain rate grows up to 100 s^{-1} at the higher investigated tool feed rate. From this point of view, in fact, it has to be said that numerical simulations with the simulation time equal to the real process time were carried out taking advantage of the experimental test brevity. So, explicit simulations through LS DYNA were carried out; in Fig. 5, the strain rate for punch velocity of 400 m/min was reported.

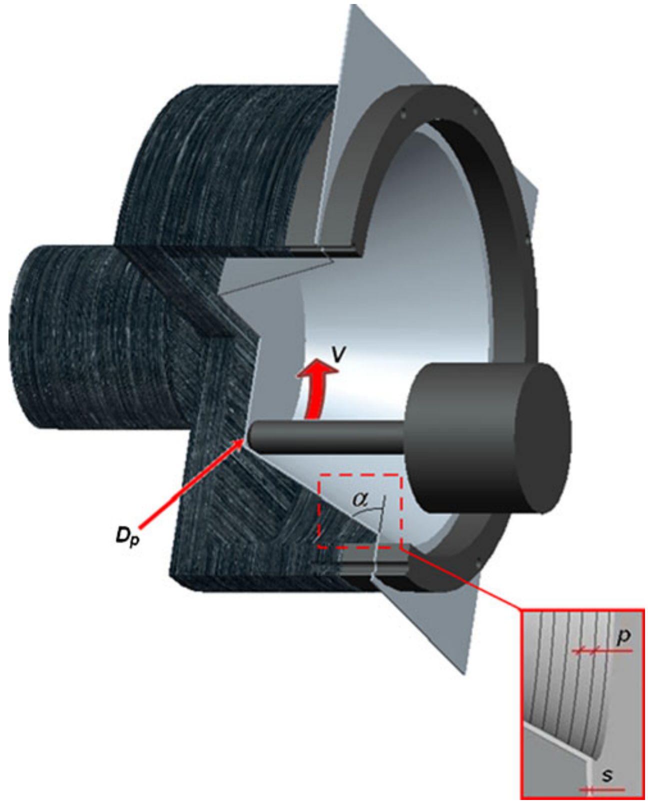


Fig. 4 Schematization of the process variables

According to the DoE method and being k=5, 16 configurations were tested for each material. The used experimental plane is displayed, in coded value, in Table 2.

4 Discussion of the results

The main issues of the present paper regarded the investigation on the process feasibility forming the blanks at high tool feed rates without decrease in material formability or in surface quality and also the impact of such approach on part accuracy. First of all, it is important to underline that all the test were safely completed, i.e., without fractures of the blanks, and this permits to claim

Table 1 Ranges of the investigate variables

Process variable	Lower bound (−1)	Upper bound (+1)
s (mm)	1	1.5
D_p (mm)	12	15
p (mm)	0.2	1
α (°)	60% · α_{max}	90% · α_{max}
V (m/min)	10	400

s Sheet thickness, D_p tool punch diameter, p tool pitch, α wall inclination angle, V tool feed rate

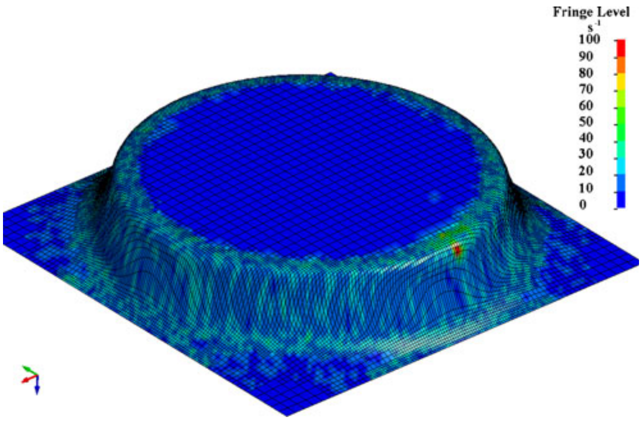


Fig. 5 Material strain rate obtained by FEM for a tool speed of 400 m/min

that formability does not decreases increasing, significantly, the tool feed, at least for the considered materials. Furthermore, at the end of each test, the surface roughness and accuracy of the part were measured and statistically analyzed. Each experiment was identified by a proper combination of the following data as specified in Table 3, where Ra_j is the average surface roughness of the manufactured part and $E_{ave\ j}$ is the average error between the incrementally formed component and the CAD one.

The experimental results were evaluated by the analysis of variance (ANOVA) technique, which allows to describe the effect of the single input factors and of their interactions on the output variable. Finally, according to the aim of the study, a particular attention was paid on the role played by

Table 2 Fractional factorial experimental plane

Test	s	D_p	p	α	V
1	+1	+1	−1	−1	+1
2	−1	+1	−1	−1	−1
3	−1	+1	−1	+1	+1
4	−1	−1	−1	−1	+1
5	−1	+1	+1	+1	−1
6	+1	−1	+1	+1	−1
7	+1	+1	+1	+1	+1
8	+1	+1	+1	−1	−1
9	−1	−1	+1	+1	+1
10	−1	−1	−1	+1	−1
11	+1	+1	−1	+1	−1
12	+1	−1	−1	−1	−1
13	−1	−1	+1	−1	−1
14	+1	−1	−1	+1	+1
15	+1	−1	+1	−1	+1
16	−1	+1	+1	−1	+1

s Sheet thickness, D_p tool punch diameter, *p* tool pitch, α wall inclination angle, *V* tool feed rate

Table 3 Investigated process factors and effects

Input (factors)					Output (response)	
s_j	$D_{p\ j}$	p_j	α_j	V_j	Ra_j	$E_{ave\ j}$

the tool feed rate and its interaction with other parameters to determine the process outputs. For such variables, the most relevant interaction diagrams were proposed to evaluate its effects.

4.1 Influence of tool feed rate on surface roughness

As far as the surface roughness Ra is concerned, few differences were highlighted for the three materials (Table 4). The tool depth step, the wall inclination angle, and the sheet thickness resulted the first order main factors. The latter issue can be easily justified since:

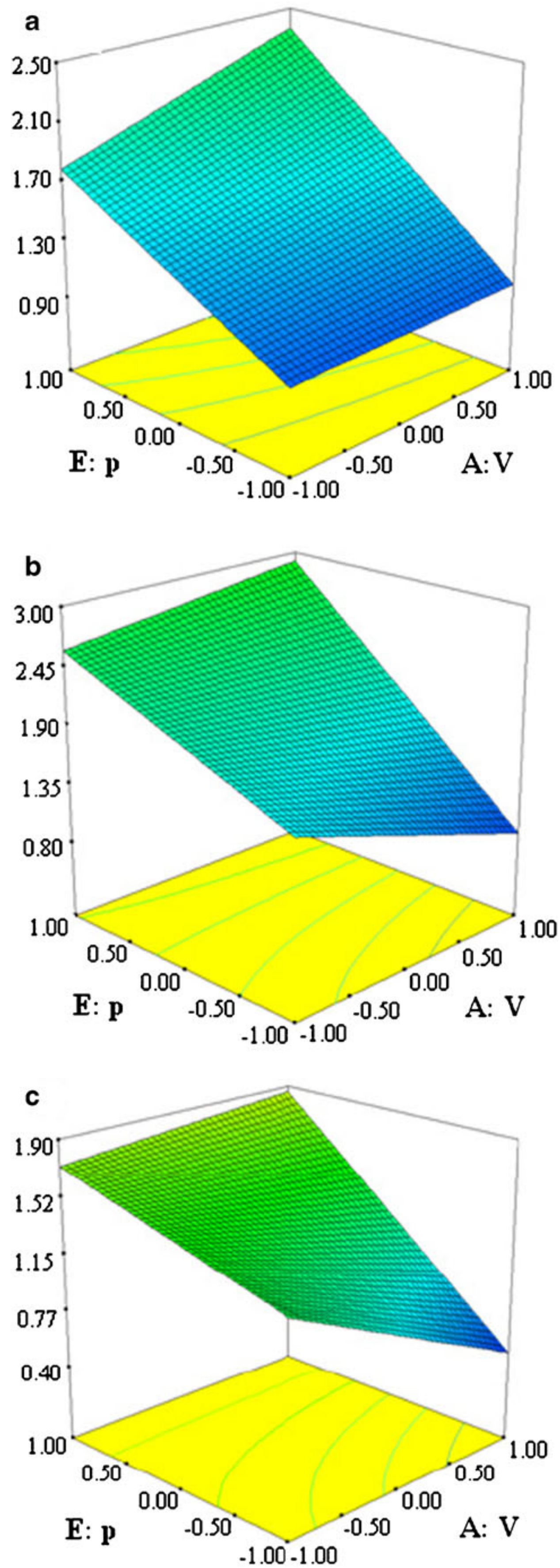
– the larger is the tool depth step, the larger is the "stair" effect on the surface, resulting in a worse surface quality;
– the smaller is the wall inclination angle, the larger is the absolute distance between two subsequent loops for a given tool pitch;
– the larger is the sheet thickness, the higher is the blank stiffness and the forces involved in the process, resulting in a more homogeneous surface.

For all the investigated materials, the role played by the tool feed rate, *V*, is never high, so that this factor could be

Table 4 ANOVA analysis for the surface roughness

Factor	Influence on Ra		
	AA1050-O	AA5754	AA6082-T6
s	Medium	High	High
D_p	High	High	Low
p	High	High	High
α	High	High	High
V	Low	Low	Medium
$s\cdot D_p$	High	NO	Medium
$s\cdot p$	Low	NO	NO
$s\cdot\alpha$	NO	NO	Low
$s\cdot V$	NO	NO	High
$D_p\cdot p$	High	NO	High
$D_p\cdot\alpha$	High	High	High
$D_p\cdot V$	NO	NO	NO
$p\cdot V$	Low	Medium	Medium
$\alpha\cdot V$	NO	NO	NO

s Sheet thickness, D_p tool punch diameter, *p* tool pitch, α wall inclination angle, *V* tool feed rate



◀ **Fig. 6** Surface roughness: interaction diagrams between the tool speed, *V*, and the tool depth step, *p*, for AA 1050 (**a**), AA 5754 (**b**), and AA6082 (**c**)

neglected in terms of influence on surface roughness. In turn, a rather strong relevance was found out for the interaction between the tool depth step and the tool feed rate ($p \cdot V$). To fully understand the last aspect in Fig. 6, the 3D interaction diagrams between the tool speed and the tool depth step are reported. As it can be easily derived, limited variations of the surface quality were determined at the varying of the tool feed rate, being the surface slope quite low; on the contrary, the response results are definitively more sensitive to small changes in the tool depth step. Concluding, the high influence of the interaction factor $p \cdot V$ is preliminarily due to the tool depth step than the tool feed rate.

4.2 Influence of tool feed rate on part accuracy

Also, the measured E_{ave} values were analyzed through ANOVA and the results are summarized in Table 5. First of all, the relevant role played by the tool diameter on the part accuracy was confirmed according to [2]: the smaller is the tool punch, the higher is the geometrical precision. The other first-order factors have a medium significance and, in this particular case, the significance of the tool feed rate cannot be completely neglected.

The response, in fact, results is sensitive to such a factor and this effect is more evident if combined with the sheet thickness and the wall inclination angle.

Table 5 ANOVA analysis for part accuracy

Factor	Influence on part accuracy		
	AA1050-O	AA5754	AA6082-T6
s	Low	Medium	Medium
D_p	High	High	High
P	Medium	Medium	Medium
α	Medium	Low	Low
V	Medium	Medium	Medium
$s \cdot D_p$	NO	Medium	Medium
$s \cdot p$	NO	Medium	Medium
$s \cdot \alpha$	NO	NO	NO
$s \cdot V$	High	Medium	Medium
$D_p \cdot p$	High	High	High
$D_p \cdot \alpha$	NO	NO	NO
$D_p \cdot V$	NO	NO	NO
$p \cdot V$	NO	NO	NO
$\alpha \cdot V$	High	Medium	Medium

s Sheet thickness, D_p tool punch diameter, p tool pitch, α wall inclination angle, V tool feed rate

The latter assumption is clearly evident as the surfaces reported in Fig. 7 are considered. For the sake of shortness, just the interaction diagrams of the tool feed rate versus the sheet thickness and the wall inclination angle for the AA1050-O are shown. The influence of tool feed rate in this case can be related to the different frictional conditions. It should be observed that the friction tends to increase with tool speed since the lubrication reduces its efficiency. As a consequence, a greater drag effect is shown and this partially increases the inaccuracy. However, even if the dependence results are statistically correct, it is important to underline that the range of variation for E_{ave} for all the investigated profile is quite small (Table 6). For this reason, as a general conclusion, it can be assessed that although the effect of tool feed rate is not negligible; such factor can be increased up to two orders of magnitude without relevant reduction in the geometrical precision of the component.

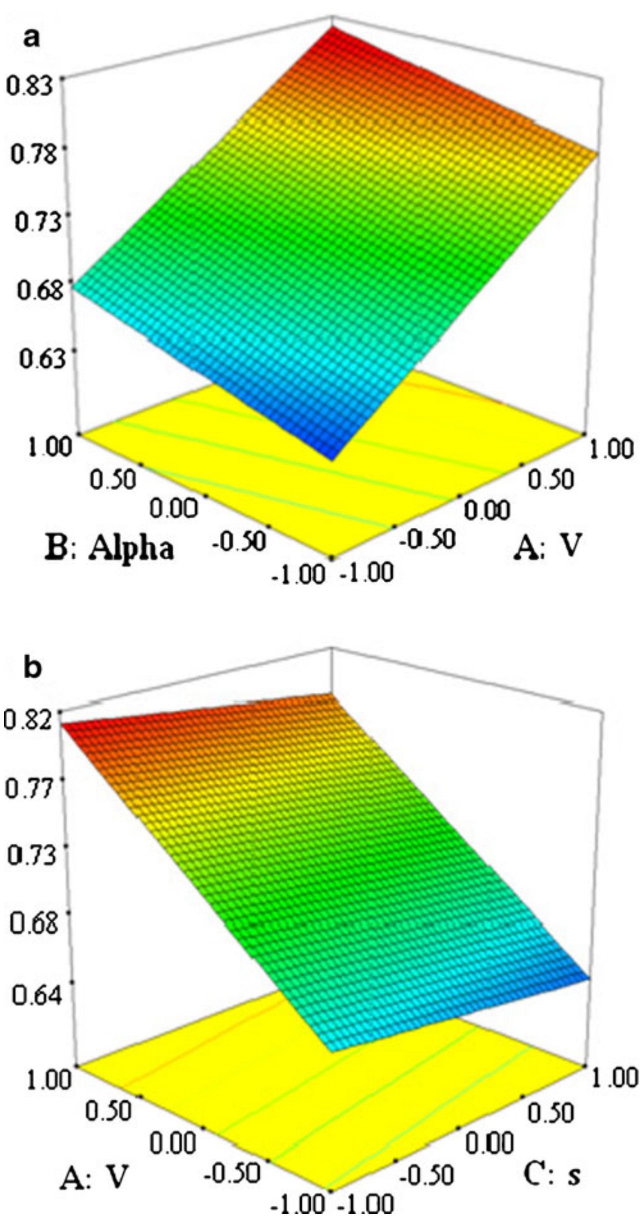


Fig. 7 Part accuracy: tool speed vs. wall inclination angle **a** and sheet thickness **b** interaction diagrams for AA 1050

Table 6 Minimum and maximum values of measured E_{ave}

	Minimum value	Maximum value
AA1050-O	0.62	0.81
AA5754	0.62	0.72
AA6082-T6	0.82	1.10

4.3 Use of backdrawing strategy to increase precision

As discussed above, accuracy in incremental forming is an open issue in the scientific community. In the past, different techniques were proposed to improve the part precision but each of them introduces a certain complexity in the process management [6]. A simple approach was used in order avoid any "intelligent design" of the tool trajectory.

The backdrawing incremental forming technique allows to obtain more precise parts just imposing the tangent tool trajectory on both the sheet sides. Normally, this alternative is not encouraged since the process duration length at least doubles but it become again interesting as high-speed incremental forming is utilized. Figure 8 shows average error maps for single slope and backdrawing incremental sheet formed parts, respectively.

In this case, a new frustum of cone with a major base of 140 mm and a wall inclination angle of 45° was manufactured working 1 mm thick AA1050-O sheets. The lower wall inclination angle exalts the springback effect and inaccuracy; for the same reason and to highlight the generalization of the proposed approach, the major base was also set smaller than the exact size of the frame, thus increasing the effects of the bending phase.

Due to this, it is important to underline that the worst result of the single IF with respect to the previous investigation has

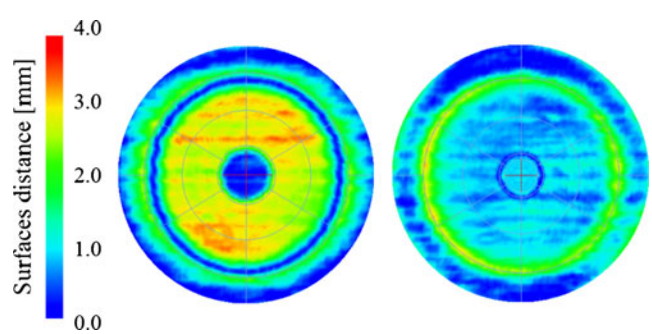


Fig. 8 Accuracy in single (*left*) and backdrawing IF (*right*) at high speed

to be justified taking into account the greater distance between the major base and the clamping equipment.

At the same time, it should be observed how the precision increases in backdrawing case (right hand side in Fig. 8), reducing the average discrepancy from 3 mm to about 1 mm.

For the sake of completeness, it is important to stress that at 400 m/min, using the tool pitch p=0.2 mm, the time to form one side of the blank is about 15 s. Thus, considering the sheet reversing using a proper clamping fixture, the part due time is about of 1 min for the whole processing cycle.

5 Conclusion

Incremental sheet forming drawbacks are mainly related to process duration and parts accuracy. The former can be overcome using a high tool feed rate, while the geometrical precision presents some criticisms. Concerning the last problem, the backdrawing approach reduces the inaccuracy without any complex tool path strategy.

At the same time, high feed rates of the tool do not affect relevant aspects, i.e., formability and surface roughness of the part. More in detail, the experimental analysis allows to summarize the following issues:

1. the surface roughness is strongly influenced by the tool depth step, the wall inclination angle, and the sheet thickness; on the contrary, the tool feed rate can be neglected;
2. as concerning the part accuracy, the effect of the tool feed rate and its interaction with the sheet thickness and the wall inclination angle cannot be ignored. However, the variation range of geometrical error for all the investigated profile is quite small; as a consequence, the tool feed rate can be increased up two orders of magnitude without relevant reduction in the geometrical precision of component.

At now, the real process limit is the maximum feed rate available on the CNC machine. However, new problems arose from the experimental investigation:

- the high relative speed between punch and material exalts the friction aspects; for this reason, the lubricant as well as the punch supporting system have to be properly set up;
- the required power is proportional to the feed rate; as a consequence, selection of suitable machine is required to fulfill the power constraint.

Concluding, the use of proper lubricant system and high-performance machines can allow incremental forming to become a technological process alternative.

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