Experimental and numerical study on optimization of the single point incremental forming of AINSI 304L stainless steel sheet

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Abstract. AINSI 304L stainless steel sheets are commonly formed into a variety of shapes for applications in the industrial, architectural, transportation and automobile fields, it’s also used for manufacturing of denture base. In the field of dentistry, there is a need for personalized devises that are custom made for the patient. The single point incremental forming process is highly promising in this area for manufacturing of denture base.

The single point incremental forming process (ISF) is an emerging process based on the use of a spherical tool, which is moved along CNC controlled tool path. One of the major advantages of this process is the ability to program several punch trajectories on the same machine in order to obtain different shapes. Several applications of this process exist in the medical field for the manufacturing of personalized titanium prosthesis (cranial plate, knee prosthesis…) due to the need of product customization to each patient.

The objective of this paper is to study the incremental forming of AISI 304L stainless steel sheets for future applications in the dentistry field. During the incremental forming process, considerable forces can occur. The control of the forming force is particularly important to ensure the safe use of the CNC milling machine and preserve the tooling and machinery.

In this paper, the effect of four different process parameters on the maximum force is studied. The proposed approach consists in using an experimental design based on experimental results. An analysis of variance was conducted with ANOVA to find the input parameters allowing to minimize the maximum forming force. A numerical simulation of the incremental forming process is performed with the optimal input process parameters. Numerical results are compared with the experimental ones.

Keywords: Incremental Sheet Forming: shapes; force; experimental; optimization; simulation.

1. Introduction

The single point incremental forming process (ISF) is an emerging process with a high industrial interest. This process is based on the use of a spherical tool, which is moved along CNC controlled tool path (figure 1). During the incremental forming process, the sheet blank is fixed in sheet holder. The tool follows a certain tool path and progressively deforms the sheet[1]. Because incremental forming is a dieless process, it is perfectly suited for prototyping, medical shapes and small volume production. One of the major advantages of the ISF process is the ability to program several punch trajectories on the same machine or robots in order to obtain different shapes without forming tools.

Stainless 304L steel sheets are used. But its high cost and difficult formability compared with aluminum make that the incremental forming of titanium sheet is little studied.
Before the incremental forming process of stainless 304L steel sheets are used is really industrialized, studies are necessary[2-6]. The ISF process indeed suffers from a big slowness, geometrical inaccuracy, a not homogeneous thickness distribution which reduces its industrial suitability[1].

During this process, considerable forces can occur. The control of the forming force is particularly important when stainless 304L steel sheets are used are used to ensure the safe use of a CNC milling machine and preserve the tooling and machinery[3].

![Figure 1. Single point incremental sheet forming process (SPIF)](image)

The aim of this paper is to determine input parameters of the process in order to minimize the maximum force achieved during the incremental forming of stainless 304L steel sheets. An experimental study, based on a Taguchi orthogonal experimental design is conducted [7]. The influence of four input parameters (sheet thickness, punch diameter, steps size, and wall angle) on the maximum forming force is analyzed to obtain the optimum values. A numerical simulation of the incremental forming process is performed with the optimal input process parameters. Numerical results are compared with the experimental ones.

2. Experimental Set up

The platform used for the experiment is a 4-axis Spinner MFG 850 milling machine given in figure 2. A multi-component FN7325 force sensor was mounted on the work-table to measure the forming forces that occur during the process. This platform was initially developed for the incremental forming of aluminium sheets and was presented in previous paper [2]. This paper concerns the incremental forming of stainless 304L steel sheets which have a size of 200 mm x 200 mm. A truncated cone with a maximum diameter of 100 mm was chosen for this preliminary study about the optimization of the incremental forming process with stainless 304L steel sheets. To produce the truncated cone, a specific assembly was performed in order to clamp the sheet on its circumference (figure 2). A semi hemispherical punch was used as forming tool. During the incremental forming process, the tool realizes a rotational movement in the horizontal plane after which it moves with a small step in the horizontal direction and then descends by a small step in the vertical direction to start a new circular contour in the next horizontal plane. A forming speed of 700 mm/min was combined with a rotation speed of 700 rpm. The punch had a 55HRC hardness and the material used was X160CrMoV12 steel. All the experiments were carried out at room temperature.
3. Experimental design optimization

The goal of this present study was to minimize the maximal forming force which occur during the process. The influence of the four following input parameters presented in figure 3 is studied:

- Sheet thickness ($t$),
- Tool punch diameter ($dp$),
- Incremental tool displacement ($\Delta z$)
- Wall angle ($\beta$).

Classical optimization methods generally require a large number of experiments. As the incremental forming process suffers from a big slowness, the Taguchi’s method and the Orthogonal Array (OA) were used to reduce the number of experiments. This method is a powerful optimization technique which allows to design the minimum number of tests to carry out [7, 8, 9] in order to reduce the time and the cost.

Figure 2. CNC milling machine used for the incremental forming process

Figure 3. Geometrical parameters of the truncated cone
An orthogonal array at two levels was chosen in this study. Table 1 presents the four forming factors and their respected levels. Eight experiments were realized according to the Taguchi’s theory. The response value is the maximal forming force which occurs during the incremental forming process. Table 2 presents the L8 orthogonal array. The response value of each trial is reported in this table.

**Table 1.** Forming factors and levels.

| Factors | Factor notation | Level 1: low value | Level 2: high value |
|---------|-----------------|--------------------|--------------------|
| t : Sheet thickness (mm) | A | 0.5 | 0.8 |
| dp : Tool diameter (mm) | B | 5 | 10 |
| Δz : Step size (mm) | C | 0.5 | 1.0 |
| β : Wall angle (°) | D | 30 | 60 |

**Table 2:** L8 orthogonal array and response values

| Experiment | A : t (mm) | B : dp (mm) | C : Δz (mm) | D : β (°) | Fz (N) |
|------------|------------|-------------|-------------|-----------|-------|
| E1         | 0.5        | 5           | 0.5         | 30        | 1620  |
| E2         | 0.8        | 5           | 0.5         | 60        | 3520  |
| E3         | 0.5        | 10          | 0.5         | 60        | 1760  |
| E4         | 0.8        | 10          | 0.5         | 30        | 2470  |
| E5         | 0.5        | 5           | 1           | 60        | 1570  |
| E6         | 0.8        | 5           | 1           | 30        | 3450  |
| E7         | 0.5        | 10          | 1           | 30        | 1870  |
| E8         | 0.8        | 10          | 1           | 60        | 3630  |

The average experimental response curve represented by the tool force versus time is illustrated in figure 4 and 5 for each design case.

**Figure 4.** Force versus-time for the E1-4 design cases
Figure 5. Force versus-time for the E4-8 design cases

An analysis of variance with ANOVA was conducted in order to analyze the effects of the four input parameters on the forming force. This technique has already been adopted by several author in order to compare the impact of various factors on response values and to define the significant factors [10,11]. Figure 6 gives a representation of the standardized Pareto chart. It shows the predominance of the sheet thickness (t) which has a significant effect on the maximal forming force. The step size (Δz) and the wall angle (β) have much less important effects on the response value. A low impact of the punch diameter (dp) on the forming force is observed.

Figure 6. Standardized PARETO chart for the forming force.

The correlation matrix given in Table 3 shows the extent of the confounding amongst the effects. A perfectly orthogonal design will show a diagonal matrix with (1) on the diagonal and (0) off the diagonal. In the case of our experimental design, there is no correlation amongst the factors. A good estimation of each factor effect can be get.
Table 3: Correlation Matrix for Estimated Effects

|                  | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
|------------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Average          | 1   | 0   | 0   | 0   | 0   | 0   | 0   | 0   |
| A:t              | 0   | 1   | 0   | 0   | 0   | 0   | 0   | 0   |
| B:Dpunch        | 0   | 0   | 1   | 0   | 0   | 0   | 0   | 0   |
| C:delta Z       | 0   | 0   | 0   | 1   | 0   | 0   | 0   | 0   |
| D:angle         | 0   | 0   | 0   | 0   | 1   | 0   | 0   | 0   |
| AB+CD           | 0   | 0   | 0   | 0   | 0   | 1   | 0   | 0   |
| AC+BD           | 0   | 0   | 0   | 0   | 0   | 1   | 0   | 0   |
| AD+BC           | 0   | 0   | 0   | 0   | 0   | 0   | 1   | 0   |

Figures 7 present the normal probability plot. The process parameters are considered significance to the experiment if there is a large angled slope of the straight line. We can see that all the points are relatively closed to the straight line and thus that the data follow a normal distribution [12].

![Normal Probability Plot for Fz_1](image)

Figure 7. Normal probability distribution for force forming.

ANOVA was used to determine the optimal input values which allow to minimize the forming force. The results are presented in the table 4.

Table 4: Optimal input values for a minimal forming force

| Input parameters | Low value | High value | Optimal Value |
|------------------|-----------|------------|---------------|
| A: t(mm)         | 0.5       | 0.8        | 0.500058      |
| B: dp(mm)        | 5         | 10         | 5.0101        |
| C: Δz(mm)        | 0.5       | 1          | 0.5           |
| D: β(°)          | 30        | 60         | 60.0          |

Minimal forming force 1540,83
4. Numerical simulation

A three dimensional finite element analysis (FEA) of the incremental forming process has been performed using the finite element solver ABAQUS explicit solver. The finite elements chosen to mesh the sheet are shell elements S4R with 4 nodes and reduced integration. The spherical tool is modelled by a rigid surface. The optimal input values of sheet thickness (t), punch diameter (dp), steps size ($\Delta z$) and wall angle ($\beta$) presented in the table 4 were used for the simulation. The elasto-plastic behaviour with isotropic hardening model is used to characterize the stainless 304L steel sheet behaviour [4]. The stress-strain material hardening parameters of the sheet are obtained using tensile tests (table 5).

|            | E (GPa) | $R_{p,0.2}$ (MPa) | Rm (MPa) | A % |
|------------|---------|-------------------|----------|-----|
| 304L       | 210     | 350               | 650      | 50  |

Figure 8. Initial and final mesh of the sheet.

The initial and final mesh of the sheet are presented in figure 8. Figure 9 gives the force versus time curve obtained by the numerical simulation.

A comparison between the numerical and experimental results is realized to validate the numerical approach. But a difference can be observed between the maximal forming force obtained numerically and the value given in table 4. We can conclude that the numerical model is not accurate enough and has to be improved. The material law used to characterize the material behaviour doesn’t take into account the general anisotropy. This result shows that it is important to take it into account.
5. Conclusion

This study about the optimization of the incremental forming process with stainless 304L steel sheets was a preliminary study. The Taguchi’s method and an Orthogonal Array based on experimental results was proposed to optimize the maximal forming force.

An analysis of variance was conducted with ANOVA. The results show a significant effect of the sheet thickness (t) on the forming force. A similar increase of the forming force was shown with increase of the steps size (Δz) and wall angle (β). A low effect of the punch diameter (dp) on the forming force is observed. Others effects due to the interaction between input parameters are shown.

Optimal input values of sheet thickness (t), punch diameter (dp), steps size (Δz) and wall angle (β) which allow to minimize the forming force were obtained with ANOVA.

A numerical simulation of the incremental forming process was performed. A comparison of the numerical results with the experimental ones has shown that the numerical model has to be improved. The Swift hardening law is not sufficient to model the material behavior. The general anisotropy has to be taken into account. This study will be pursued in future works.

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Figure 9. FEA forming force (Fz) for the optimal input parameters values
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