Analysis of forming forces at SPIF using Taguchi method

Mihai-Octavian POPP[1], Sever-Gabriel RACZ[1*], Mihaela OLEKSIK[1], Claudia GÎRJOB[1], Cristina BIRIȘ[1],

[1] "Lucian Blaga" University of Sibiu, Sibiu, România
*gabriel.racz@ulbsibiu.ro

Abstract. Incremental sheet metal forming process has seen one of the highest increases in diversity in the last years. Single point incremental forming (SPIF) has become more attractive due to multiple benefits it possesses over other conventional cold forming processes such as deep-drawing. However, the process has yet to arise in the large-scale industrial implementation because of its drawbacks such as high production time and low accuracy, which lead to prototype production.

A very important aspect for this manufacturing process is the analysis of the form-ing forces in terms of process energy especially when using industrial robots.

The aim of this paper is to investigate the influence of material and vertical step over the forming forces. Thus, aluminum and steel sheets with a thickness of 0,8mm were incrementally deformed as a truncated cone with an angle of 60°, at a depth of 30mm. Experiments were performed using a KUKA KR 210-2 robot which allows to measure the forces using a piezoresistive sensor.

After performing the analysis of the forming forces using the Taguchi method, it can be observed that the material has the highest influence.

Keywords: single point incremental forming, forming forces, Taguchi Method.

1 Introduction

Incremental forming process has become in recent years a competitive process among cold plastic deformation processes, due to its high flexibility. It is well suited for rapid prototype parts as well as automotive car body parts. The process can be performed with a few components involved such as: retaining rings which are used for the fixture of the sheet blanks, a CNC machine or an industrial robot which supplies the necessary energy for sheet blanks deformation and a tool in form of a simple punch that follows a predefined toolpath by the user [1]. Other components may be involved in the process, especially for the analysis of deformation mechanism, such as various sensors, thermal cameras and 3d optical measurement systems for stresses and strains. Even though, at first glance, the process presents a good number of advantages over its main competitor, deep-drawing process, it shows two important drawbacks which are: low geometric accuracy due to the fact that it lacks a supporting die and the manufacturing times are quite high [2]. Geometric accuracy is one of the main drawbacks of SPIF process, thus researchers tried various methods to overcome it, such as modifying the process

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parameters like tool diameter, step depth and toolpath. Najm et al. [3] showed that decreasing the tool diameter leads to an increase in formability. One intensive study regarding the forces involved in incremental forming process has begun since the first researches about this process and it is still in development due to the arise of new alloys for every base material.

A better perspective on mechanical deformation can be obtained by checking the deformation forces. In other words, product design and process improvement can be done by predicting deformation forces. This can be determined experimentally as shown in numerous studies. Force measurement systems have been developed for incremental forming processes using sensors [4]. A torque mass was used to measure the components of the forces encountered during the process by Duflou et al. to investigate the impact of the vertical pitch, the punch diameter and the wall angle on the forming forces [5].

In a more detailed analysis, it can be seen that the vertical forces of single point incremental forming process (SPIF) depend on the type of toolpath [6]. Based on the impact of the variables on the process, Ambrogio et al. developed a strategy to monitor the forces so as to prevent material failure [7]. In studies conducted by Esmaeilpour et al. and Flores and collaborators using finite element analysis, it was shown that the functions used for the yield criterion and the hardening laws of influence the prediction of forces [8], [9] , [10].

Bagudanch et al. conducted a thorough investigation regarding forming forces of 0.8 mm thick stainless steel AISI 304 sheet blanks and showed that forces of up to 3.5kN were reached during the process. [11]. In another paper, Badreddine et al. investigated the forming forces of AA1050-O sheet blanks and showed that by increasing process parameters such as sheet thickness, wall angle and vertical step leads to an increase of maximum forces during process. [12]

2 Experimental tests

2.1 Material and equipment

For the experiments performed, sheet blanks with a size of 250x250mm and a thickness of 0.8mm were used. The material used for the tests is DC01 steel which according to standard EN10130-2006 has the chemical properties shown in Table 1.

Table 1. Chemical composition of DC01 steel.

Composition	C	Mn	P	S
Wt %	0.12	0.6	0.05	0.045

Taking into account the purpose of this experimental research, for the study of the forming forces during the single point incremental forming process (SPIF) and the analysis of the obtained results regarding the precision of the parts, the experimental setup shown in Figure 1 was used. The sheet blanks were fixed with a special support built within Metal Forming Research Center from University “Lucian Blaga” of Sibiu.

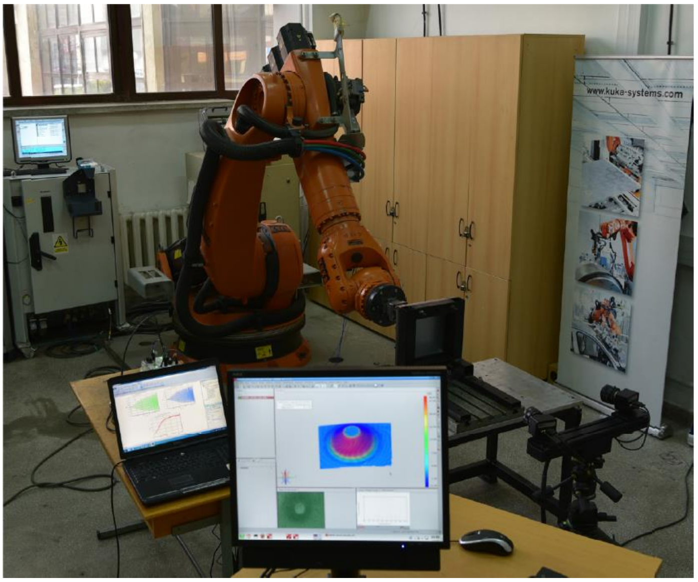


Fig. 1. Experimental test setup.

The KUKA KR 210-2 industrial robot was used to deform the sheets. The structure of this robot is serial, having 6 kinematic rotating couplings that introduce a degree of freedom each to the structure, so the robot has 6 degrees of freedom which gives it a high flexibility compared to a numerically controlled machine (CNC). The robot has a deformation capacity of up to 2000 N.

The forces were measured using a piezoresistive force transducer from PCB Piezotronics, model type 261A13. It has a capacity of 70 pF for all 3 channels and can measure maximum forces of up to 17.7 kN on the X and Y axis, respectively 44.48 kN on the axial direction Z (which coincides with the axis perpendicular to the sheet blank). It provides a unified output signal that is transmitted to the MX840B QuantumX data acquisition system from HBM.

In this case, we used a signal sampling frequency of 50 Hz for the 3 components of the force (Fx, Fy and Fz) measured during the incremental forming process, because using a higher frequency involves the generation of very large files, especially in the case of parts where complex trajectories were used and the processing time exceeded 20 min. The software used for measuring, saving, real-time monitoring and force analysis was Catman provided by National Instruments.

2.2 Design of experiments

Taguchi method was used to find out the factors that influence the forces. This is a statistical method designed to improve product quality and is based on combining quality engineering with statistical methods. It has been shown to be more efficient than other methods of experiment planning, being a derivative of the factorial experiment method. It is used to calculate the mean effects of factors and interactions [13].

For the design of experiments (DOE) plan by Taguchi method, the following factors were taken into account: the punch diameter, the vertical step, the wall angle and the final depth of parts, each of them having two values. The 2^3 combination variant of the Taguchi method was then chosen, resulting in 8 tests. These are shown in Table 2.

Table 2. Design of experiments with Taguchi method.

Nr. Crt.	Punch diameter	Step	Wall angle	Depth	First run		Second run	
					Fz_1	Fy_1	Fz_2	Fy_2
1	6	0.25	50	30	1.003	0.371	1.011	0.372
2	6	0.75	60	30	1.180	0.79	1.167	0.781
3	6	0.75	50	40	1.119	0.544	1.132	0.539
4	6	0.25	60	40	1.016	0.872	1.026	0.877
5	10	0.75	50	30	1.339	0.595	1.330	0.588
6	10	0.25	60	30	1.124	0.512	1.107	0.518
7	10	0.25	50	40	1.141	0.462	1.150	0.453
8	10	0.75	60	40	1.316	0.682	1.292	0.675

3 Results and discussion

During the experiments, forces over three axes were measured: Fx, Fy and Fz. Table 2 shows the maximum forces obtained in the Y and Z directions, because the forces over X and Y directions have almost the same maximum values. The 8 tests were repeated twice to have a good knowledge of which factors influence the forces. Figure 2 shows all forces measured for combination 5.

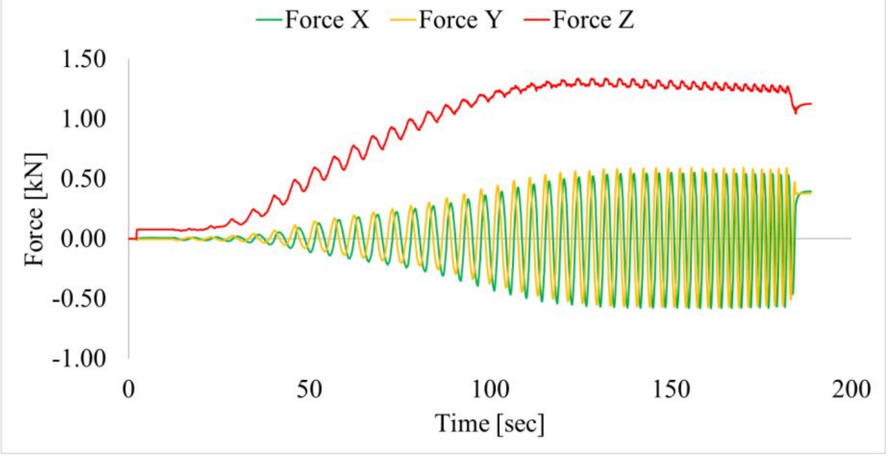


Fig. 2. Forces over X, Y and Z axis for combination 5.

Following the analysis performed using the Taguchi method and with the help of Minitab software, the response tables for signal to noise ratios (SN ratios) are obtained for both Fz and Fy over all four factors which are presented in table 3 and table 4.

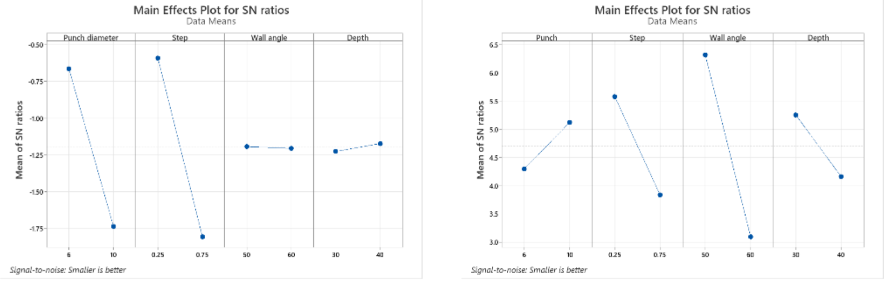
Table 3. Response table for SN ratios of Fz1, Fz2 versus Punch diameter, Step, Wall angle and depth.

Level	Punch diameter	Step	Wall angle	Depth
1	-0.6637	-0.5926	-1.1931	-1.2262
2	-1.7349	-1.8060	-1.2055	-1.1724
Delta	1.0713	1.2134	0.0124	0.0538
Rank	2	1	4	3

Table 4. Response table for SN ratios of Fy1, Fy2 versus Punch diameter, Step, Wall angle and depth.

Level	Punch diameter	Step	Wall angle	Depth
1	4.296	5.580	6.318	5.255
2	5.122	3.838	3.099	4.163
Delta	0.825	1.742	3.219	1.092
Rank	4	2	1	3

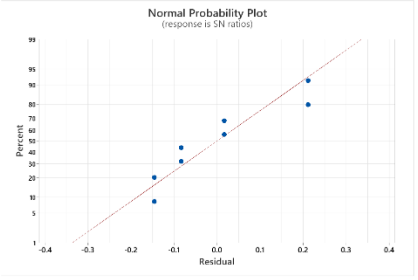
For the analysis of the Taguchi method, the response "smaller is better" was chosen because it is desired that the forces during the incremental forming process to be minimal. Thus, in Figure 3 a) is presented the main effects plot for SN ratios for Fz forces, whereas in Figure 3 b) is presented the main effects plot for SN ratios for Fy forces. In the case of Fz forces we can observe that the vertical step has the highest influence, followed by punch diameter, part depth and in the last place with little to no influence is the wall angle of the part. On the other hand, Fy forces are mainly influenced by the wall angle of the part, so for a 50° part the Fy forces are smaller than in the case of 60° part. The second factor which influences the Fy forces is represented by vertical step, followed by part depth and punch diameter.



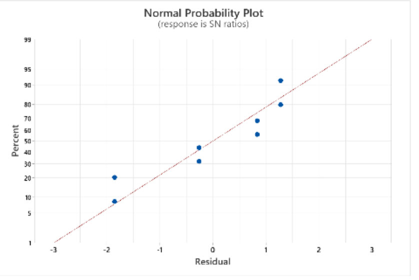
a) b)

Fig. 3. Main effects plot for SN ratios for a) Fz forces; b) Fy forces.

Figure 4 presents the normal probability plot for a) Fz forces and b) Fy forces. It can be observed that there is no obvious pattern.



a)



b)

Fig. 4. a) Normal distribution for SN ratios for a) Fz forces; b) Fy forces.

4 Conclusions

Various methods for planning results are useful for the most accurate analysis of the factors that influence the forces in the process of incremental deformation. One of these methods that allows an easier understanding of the parameters influence is Taguchi method.

In this work, 8 combinations of punch diameter, vertical step, wall angle and depth were planned using the Taguchi method. Each of these 8 combinations was repeated twice to have a more accurate overview of the influence of the 4 parameters.

From the analysis of the experimental data, it can be seen that the Fz forces decreases with the decrease of the vertical step and punch diameter, whereas the other two factors have an insignificant influence. Instead, while considering the Fy forces, the most significant influencing factors are the wall angle, the vertical step, and the other two factors presents a lower influence.

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