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FORCE ANALYSIS IN SINGLE POINT INCREMENTAL FORMING FROM PROCESS PARAMETER VARIATION

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Abstract. *The study of the manufacturing process is motivated by the growing need of industries for higher levels of accuracy and precision for their products in the shortest time. For this reason, the incremental sheet forming process has been used for produced small batch sizes that do not require jigs or dies. This type of forming processes highlights by reduced cost of manufacturing and is more versatile and flexible. The incremental sheet forming shown as an important technique in the maintenance and prototype sector since it eliminates the need for a die forming or specific tools. Due to its ease and low cost, this process stands out in the manufacture of parts, e.g., at aeronautical sector. This work aims to analyze the forming forces during the forming of galvanized steel with problems single point incremental sheet forming (SPIF) due to variation of three parameters process: spindle speed tool, feed rate, step down. For the experiments was used a dynamometer, and the forces were measured in xyz axis. The material used was a galvanized steel sheet with 1,25 mm of thickness fixed in CNC milling machine. The single point increment was performed by a rotating cylindrical tool. The impacts of the interactions of these conditions were verified using the technique of full factorial design of the experiment (DOE) followed by the analysis of variance (ANOVA), allowing to plot the force variation graph. Finally, it has been concluded that galvanized steel presents good formability for the tested parameters. Furthermore, the range of forming mean force on the experiments ranged from 407 N to 1498 N. When doubling the spindle speed tool, regardless of the increase or reduction of the step down, the forming forces decrease in all directions. The force signal (Fx, Fy, Fz) was growing until the stability due the increased progressive contact area between the tool and the sheet metal. The most influence process parameter at mean forces was feed rate. For future works expects to analyze the surface quality of the part and the relationship with the contact frequency obtained by the forming force signals.*

Keywords: *Sheet metal forming, Single point incremental stamping, Galvanized steel, Forming forces.*

1. INTRODUCTION

The growing need of industries to select manufacturing processes that accurately achieve the designed product, with the least possible investment of time, labor and raw material, has justified the increasingly in-depth study of manufacturing techniques.

Given this market requirement, we have the dieless forming process that can be used to manufacture parts that do not require forming to be performed in only one direction. This variation of the forming process has the advantage of reduce tooling cost and the fact that it is extremely versatile and flexible.

According to Helman (2015), the practice of mechanical forming has relied mainly on the empirical method and know-how has traditionally been the method for solving problems. This way of working is satisfactory as long as the problems to be solved are understood within the experience of the researcher.

In the metallurgical industry, the dieless forming technique has been developed and applied recently. The basic characteristic of mechanical forming is the application of external force to the raw material, forcing it to acquire the desired shape by plastic deformation, that is, it is related to all processes that exploit the plastic deformability of materials (Edwards et al, 2010), and in the case of the process used in this research, without the use of a matrix. Due to this characteristic of absence of support, the modality has the potential to significantly reduce the cost of small batches and prototypes, since the investment in customized tools can be avoided.

The present work aims to analyze the behavior of the forming forces during the forming of galvanized steel when subjected to the dieless forming technique and its SPIF (single point incremental) variation. For this analysis, parameters such as angular velocity, feed and vertical pitch were established for each test and, with the help of a month dynamometer, the forces were measured in the XYZ directions. The impacts of the interactions of these conditions were checked using the full factorial design of experiment (DOE) technique followed by analysis of variance (ANOVA), allowing to trace the behavior of the forming forces.

1.1 Incremental Stamping

One of the oldest manufacturing processes, about 4,000 years BC, mechanical forming consists of changing the geometry of the material, more specifically the modification of a metallic body, which will be studied in this work. According to FILHO et al. (1991), mechanical forming processes consist of shape modifications caused by the application of external stresses.

In the course of this research, plastic forming will be used, for which the applied stresses are generally lower than the breaking strength limit of the material and this study is important because more than 80% of all metal products produced are subjected, in one or more stages, to such a process, as stated by FILHO et al. (1991).

According to FILHO et al. (1991), the deep stamping of sheets is characterized by achieving the final shape of a cup from a circular outline, or disk. The metallic disk, by means of the action of the punch in its central region, deforms towards the circular cavity of the die, at the same time that the flap or flange, that is, the part where the punch does not act, but only the subjector, moves towards the cavity (Figure 1).

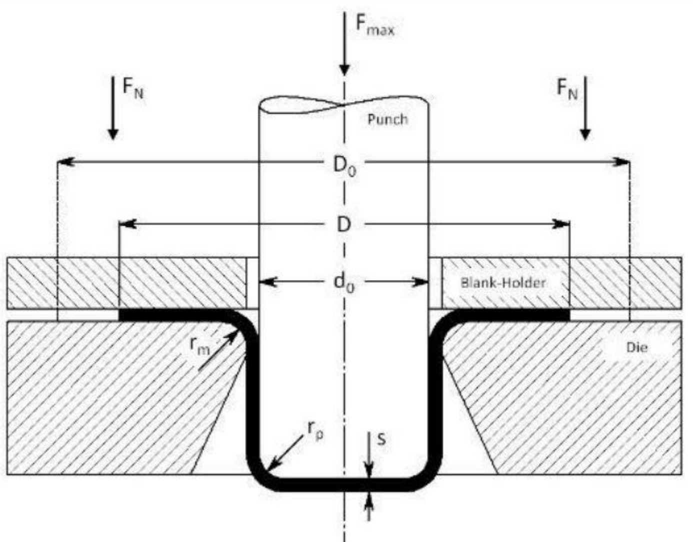

Figure 1. Regions of the cup under stamping with different stress states. FOLLE et al. (2019).

Within this group we have incremental stamping which is a process applied to the manufacture of small-scale parts and the prototyping of components under development, as stated by GARG et al. (2016). According to PARK et al. (2003), there are great advantages in this process over conventional stamping, with the lower cost of manufacturing the tooling and obtaining higher stamping limits (Figure 2).

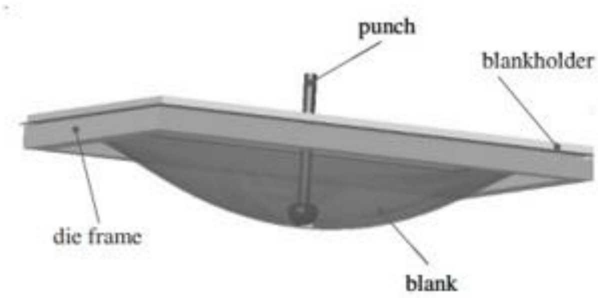

Figure 2 - Scheme of the incremental stamping process (STRANO, 2003).

It is possible to distinguish between single point incremental stamping (SPIF-Single Point Incremental Forming) and double point incremental stamping (TPIF - Two Points Incremental Forming) (ATTANASIO, CERETTI and GIARDINI,2006). However, to achieve precise shapes in incremental stamping, specific lower support is used in the desired format,which can be with axial or asymmetric symmetry, indicated to obtain complex and organic surfaces. This support, in turn, can be positive (bounce) or negative (cavity). (ALLWOOD, BRAMLEY, et al., 2005), (HIRT, JUNK, *et al.*, 2005). Thefollowing figure illustrates the modalities mentioned.

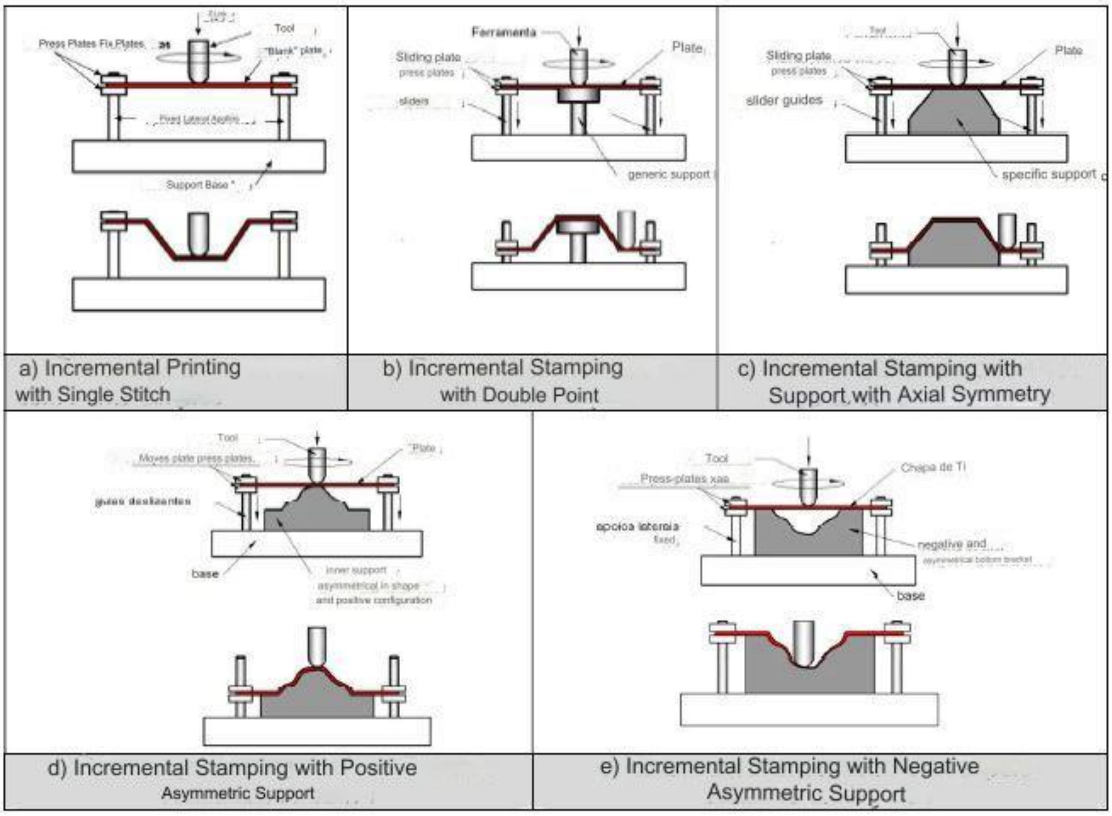

Figure 3 - Modalities of incremental stamping. Adapted from (CASTELAN, 2010)

Single-point incremental stamping (SPIF), defined by the acronym SPIF - Single-point Incremental Forming, was proven to be viable for the production of small batches of sheet metal parts, in a wide range of materials and geometric shapes, by a group of international scientists in 2005 (JESWIET, MICARI, *et al*., 2005).

Because it does not use lower support, this modality is commonly called *dieless* - "without matrix", as predicted by Leszak in 1967. (CASTELAN, 2010), adds that because there is no lower support point, the shape of the final piece is determined only by the displacement of the tool in the 3 axes (X, Y and Z). The plate is fixed in lateral supports that maintain constant height in relation to the base. (HUSSAIN, DAR, *et al*., 2007), cites in his studies, that these fixing elements, avoid the movement of the plate during the process, culminating in its plastic deformation.

1.1.1 INCREMENTAL STAMPING PARAMETERS

This research analyzed the parameters feed rate, tool rotation and vertical pitch during the *dieless forming* process and their influence on the forming forces. The experimental trials were further expanded to tests with and without lubrication.

The Vertical Pass refers to the distance between each complete tool path (contour) in the direction of the Z axis of the machine. It is a parameter, in the work published by Jeswiet *et al*. (2005) reports that the greater the Vertical Pass, the more the formability decreases and the roughness and forming force increase.

Jeswiet *et al*. (2005) also claims that the increase in tool rotation can influence the surface finish of the resulting part as well as its formability. The higher the rotation, the worse the surface finish of the resulting part should be, since the tool travels in the same stamping point a larger circumference, and it may even be the case of multiple turns, depending on its feed rate.

Lubrication seeks to reduce the shear that occurs due to the contact between work tool and plate. With this, it can play an important role in tool life, in the surface finish of the part and in reducing the heating of the plate during the stamping process. The great variation of lubrication, as its use is considered or not, is preponderant in the conformability of the material (Skjoedt, 2008).

The feed is characterized as the translation speed of the tool in the stamping plane of the plate, that is, how fast the tool travels the prescribed trajectory for forming the part. The higher the feed, the shorter the test time and the shorter the contact time between the tool and the stamping point, which can have a negative influence on its formability, because, according to Jeswiet (2005), the greater the ease of the steel to continue being formed the lower the feed throughout the process without its physical integrity being impaired.

1.1.2 INCREMENTAL STAMPING PARAMETERS

Figure 4 shows the force components in Cartesian coordinate system. Fxy is the force in the plane and Fz is the axialforce in the vertical downward direction of the tool movement.

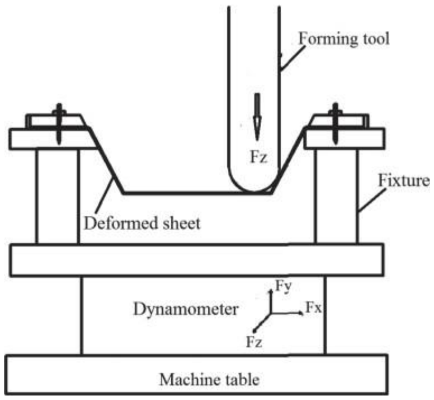

Figure 4: Components of forming force. KUMAR, *et al*. (2019)

As predicted by Aerens et al. (2009), during the SPIF process, the "stable" signal - with little oscillation, and in the positive plane of the forces - was observed for FZ and two sinusoidal signals for FX and FY. The authors explain that the sinusoidal aspect of the radial forces results from the symmetrical format of the experiments, where, at a given moment, the load cells are acquiring traction signals, and at the next moment, compression signals, characterizing such aspect.

2. METHODOLOGY

The experiments were carried out in the Machining Laboratory, at room temperature, using the single point incremental forming process and with the use of the following materials, equipment and software:

- Universal (CNC) milling machine, ROMI brand, model U-30;
- Cylindrical tool made of SAE 52100 steel;
- Galvanized steel sheet with a thickness of 1.25 mm;
- Table dynamometer linked to the sheet metal press;
- Own algorithm generated in the free software Scilab for generating the raw signal of the force (N) of conformation, as well as the treatment of the information collected in the tests;
- The impacts of the interactions of these conditions were checked using the full factorial design of experiment (DOE) technique followed by analysis of variance (ANOVA).

The main purpose of the analyses is to study the individual behavior of the forming forces, with the variation of the parameters controlled at each test, as shown in Table 1.

Table 1. Parameters used in each test.

TEST CONDITIONS			
TEST	**ANGULAR VELOCITY (RPM)**	**ADVANCE (mm/min)**	**VERTICAL STEP (mm)**
1	75	800	0.8
2	150	800	0.5
3	75	1200	0.5
4	150	1200	0.8
DRY	10	800	0.5
DRY2	10	1200	0.5
DRY3	10	800	0.8

Source: Own (2023)

The results were analyzed and discussed with the support of graphs and tables with the data generated by the algorithm created.

3. RESULTS AND DISCUSSIONS

The analysis of the results described below, depicts the data obtained from the SPIF (single point incremental stamping - *dieless forming*) experiments performed on galvanized steel, following the methodology described above. Alltests had as common parameters the material, thickness and geometry of the sheet, with variation of the feed, angular velocity and vertical pitch, with or without lubrication. Although, during the tests it is possible to follow the change in the value of the individual forces, the performance of the forces when comparing the tests is only possible at the end of the experiments.

For the test conditions cited in Table 1, with tests 1 to 4 being performed with lubrication, and DRY to DRY 3, without lubricating oil, the forming force values in Tables 2 and 3 were obtained.

Table 2. Values of individual forces obtained in the tests with lubrication

RESULTS OBTAINED			
TEST	FORCE X (N)	FORCE Y (N)	FORCE Z (N)
T1R1	607	599	1495
T1R2	610	601	1498
T2R1	500	496	1282
T2R2	510	516	1232
T3R1	625	635	1357
T3R2	614	624	1366
T4R1	445	441	1189
T4R2	450	447	1192

Source: Own (2023)

Table 3. Values of individual forces obtained in the tests without lubrication

RESULTS OBTAINED			
TEST	FORCE X (N)	FORCE Y (N)	FORCE Z (N)
DRYR1	552	548	814
DRYR2	556	553	818
DRY2	601	576	1407
DRY2R2	604	581	1411
DRY3	413	407	1261
DRY3R2	416	412	1265

Source: Own (2023)

Figure 5 shows the behavior of the forming forces when varying or not the parameters investigated in each test. This variation was established by comparing the tests.

COMPARISON BETWEEN TESTS	ANGULAR SPEED (RPM)		FEED (mm/min)		VERTICAL PITCH (mm)		CONFORMING FORCES					
							Fx		Fy		Fz	
1 and 2	INCREASED	100%	KEPT AT 800 (mm/min)		REDUCED	37,5%	REDUCED	17,6%	REDUCED	17,2%	REDUCED	14,2%
3 and 4	INCREASED	100%	KEPT AT 1200 (mm/min)		INCREASED	60%	REDUCED	28,8%	REDUCED	30,6%	REDUCED	12,4%
1 and 3	KEPT IT AT 75 RPM		INCREASED	50%	REDUCED	37,5%	INCREASED	3%	INCREASED	6%	REDUCED	9,2%
1 and 4	INCREASED	100%	INCREASED	50%	KEPT AT 0.8 mm		REDUCED	26,7%	REDUCED	26,4%	REDUCED	20,5%
2 and 3	INCREASED	100%	INCREASED	50%	KEPT AT 0.5 mm		INCREASED	25%	INCREASED	28%	INCREASED	5,8%
2 and 4	KEPT IT AT 150 RPM		INCREASED	50%	INCREASED	60%	REDUCED	11%	REDUCED	11,1%	REDUCED	7,2%
DRY and DRY 2	KEPT IT AT 10 RPM		INCREASED	50%	KEPT AT 0.5 mm		INCREASED	8,9%	INCREASED	5,1%	INCREASED	72,8%
DRY and DRY 3			KEPT AT 800 (mm/min)		INCREASED	60%	REDUCED	25,2%	REDUCED	25,7%	INCREASED	54,9%
SECO 2 and SECO 3			REDUCED	33,3%	INCREASED	60%	REDUCED	31,3%	REDUCED	29,3%	REDUCED	10,4%

Figure 5: Behavior of the forming forces with the change of parameters. Own (2023)

The greatest reduction in force in the x-coordinate (31.3%) was identified in the comparison between tests without lubrication with a rotation of only 10 RPM, a reduction in the advance by 33.3% and an increase in the vertical step by 60%. The greatest increase in Fx (25%) occurred between the tests with lubrication, 100% increase in angular velocity, and 50% increase in feed with maintenance of the vertical step at 0.5 mm.

Regarding Fz, its greatest reduction (20.5%) was identified when comparing tests with the use of lubricant and a 100% increase in angular velocity and 50% increase in feed rate, while maintaining the vertical pitch at 0.8 mm. On the other hand, the most significant increase in z-forming force, 72.8%, occurs when there is no lubrication, the angular velocity and vertical pitch are maintained, respectively, at 10 RPM and 0.5 mm, and the feed is increased by 50%.

When analyzing the forming force Fy, it is noted that the greatest reduction (30.6%) occurs with the use of lubrication, maintaining the feed at 1200 mm/min, and increasing the angular velocity by 100% and the vertical pitch by 60%. Regarding the largest increase (28%), it is possible to identify it in the comparison between tests with lubricating oil, increasing the angular velocity and the feed by 100% and 50%, respectively, and maintaining the vertical step at 0.5 mm.

The axial force (Fz), for the tests with lubrication, was analyzed by the ANOVA tool, as it has the most significant values.

	ANOVA Matrix						
Factor	**Factors**	**GL**	**SQ**	**Percentage Contributio**	**MQ**	**Fo**	**P**
Angular Velocity	**A**	1	156618	75,08%	156618	945,975	1,36E-09
Advance	**B**	1	46764,1	22,42%	46764,1	282,456	1,59E-07
Angular Speed x Feed	**AxB**	1	3164,06	1,52%	3164,06	19,111	2,38E-03
Vertical Step	**W**	1	150,063	0,07%	150,063	0,90638	3,69E-01
Angular Velocity x Vertical Pitch	**A x C**	1	217,563	0,10%	217,563	1,31408	2,85E-01
Feed x Vertical Pitch	**B x C**	1	217,563	0,10%	217,563	1,31408	2,85E-01
Angular Velocity x Feed x Vertical Pitch	**A x B x C**	1	150,063	0,07%	150,063	0,90638	3,69E-01
	Error	8	1324,5	0,63%	165,563		
	Total	15	208606	1			

Figure 6. Analysis of variance of axial force in tests with lubrication, by ANOVA Matrix. Own (2023)

4. CONCLUSIONS

From this work, it can be concluded that the galvanized steel, with 1.25 mm thickness, presented good formability for the tested parameters, since in no test was rupture experienced. It is also noteworthy that the range of forming force measured in the experiment ranged from 407 N to 1498 N.

When doubling the rotation speed, it is identified that, regardless of the increase or reduction of the vertical pitch, the forming forces decrease, in the three directions. This conclusion corroborates with the studies cited in the literature review article by KUMA *et al.* (2019), where it cites that in 87% of the investigations, made in the literature, show that the forming forces decrease with the increase of the spindle speed. According to Davarpanah *et al.* (2015), this is due to the fact that higher spindle speed increases the friction at the sheet-tool interface, which results in increased ductility of the material. Therefore, a higher spindle speed can form thicker sheets and reduced forming forces.

In order to maintain the integrity of the material, when performing the tests without lubrication, the angular velocity was significantly reduced, and maintained, at 10 RPM. Due to the adaptation of this parameter, the existence or not of the lubricant did not significantly affect the forming forces.

Regarding the feed rate, significant increases in forces in all directions were identified when increasing this indicator. This finding confirms the tendency of forming forces to increase with increasing feed rate, according to KUMA *et al.* (2019).

On the sign of the force, an increasing behavior was observed until stability due to the increase of the contact area between the tool and the piece. In relation to the feed rate, significant increases in forces in all directions were identifiedwhen this indicator increased. For future work we intend to analyze aspects of the quality of the workpiece surface and the relationship with the contact frequency obtained by the forming force signals.

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