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STUDY OF THE APPLICABILITY OF SPIF IN ALUMINIUM PLATES

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Abstract. *The emergence and continual development of new techniques of rapid prototyping is an established reality in actual manufacturing metal-mechanical world industry. Among these techniques, Sheet Metal Incremental Forming has gained prominence for being an efficient solution in the manufacture of parts in small lots, prototypes or complex geometry, which sometimes prevents large investments in tooling of a conventional process. Comes against the fact those characteristics of the machinery involved is usually found in manufacturing industries, which makes their use more feasible. Therefore, it is necessary to know the parameters inherent to this technique for accurate characterization of materials processed by it. In the present study will investigate the main parameters of this technique when aluminum sheets used commercially in the metalworking industry are processed in three different geometries. For this, will be applied Single Point Incremental Forming - Negative Dieless (SPIF) technique in order to understand the main parameters of the process (work angle, vertical step size, variation of plate thickness) as a result of using these materials.*
Keywords*: Sheet Metal Forming, Incremental Sheet Forming, Single Point Incremental Forming, SPIF*

1. INTRODUCTION

According Jeswiet (2001), this process is used to forming sheet metal parts into complex shapes without the use of dies, using a metal tool for this puntual contact, mounted on a machining center, in order to plastically deform this blank by part of the movement and/or tool, especially in the vertical plane. The process, generally called Incremental Sheet Forming (ISF) is also known, when the forming tool is of a single contact, as the Single Point Incremental Forming (SPIF), or, depending on how the part is formed (internally or externally), the process can still be called Negative or Positive. According to the geometry, its possible to name it as symmetrical or asymmetrical. Unless otherwise comment, this article deals with applications of the SPIF process, Negative and Symmetrical.

The tool is initially positioned on the piece to be obtained, then moving according to a predetermined trajectory, according to the final form to be reached. Each trajectory described, there is increasing strain to be applied. Park *et al* (2003) illustrate, schematically, in Fig.1, the process and its possible tools.

Figure 1. Single Point Incremental Forming process (Dieless, Negative and Symmetrical)

2. FUNDAMENTALS, PARAMETERS AND CHARACTERISTIC OF THE PROCESS

The historical development of the ISF has shown that major advances in the process occur when the material is properly characterized to be used by him, and the main characteristic being determined is its limit of formability. Within the studies that bring a theoretical light on the SPIF, the work of Martins *et al*, "Revisiting the fundamentals of single point incremental forming by means of membrane analysis" (2008) gets highlighted in the characterization of the main quantities involved, as illustrated in Fig 2.

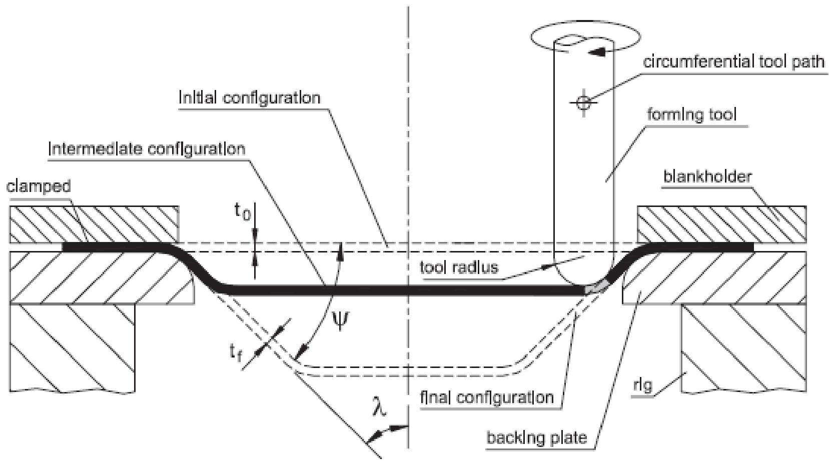

Figure 2. SPIF process representation and main variables

Where:
- t_0: initial thickness of the plate;
- t_f: final thickness of the plate;
- ψ: working angle between the conformal surface and initial configuration of the plate;
- λ: semi-cone angle to be worked.

2.1. Advantages and Disadvantages of SPIF

Jeswiet *et al* (2005) show the main advantages and disadvantages of SPIF:

Advantages

- Parts of disposal can be obtained directly from an interface CAD/CAM, minimizing the time/cost of production and making it feasible to apply to lots or small scale unit;
- The process does not require use of dies, for most applications;
- Changes in specific parts of the project are easily implemented, ensuring its flexibility;
- Rapid Prototyping in metals, usually difficult to implement, it is easy in this process;
- The small plastic deformation induced contributes to the increased formability checked in using the process;
- A conventional CNC can be used to settle a plate;
- The size of the piece being conformed is limited by the available space on the machine, not requiring larger forces to forming these parts;
- The surface finish is usually very satisfactory;
- The operation is relatively quiet;
- The process allows deep drawings.

Disadvantages

- Process time is much larger than a conventional deep drawing process. Because of this, to be economically feasible, the SPIF must be applied to manufacturing parts that require small batches;
- The drawing of right angles does not occur in a single pass, but in multi-stage;
- Springback occurs.

Jeswiet *et al* (2005), as cited in Martins *et al*, in the work "Revisiting the fundamentals of single point incremental forming by means of membrane analysis" (2008), show that the experimental investigations lead to the conclusion that the formability associated with the process can be defined in relation to four major parameters: plate thickness, size of the vertical increment; speed and radius of the tool. The influence of the first two parameters is commonly explained by applying the sine law in relation to thickness, i.e., $t_f = t_0$ sen (λ). The tool speed influences the conditions of formability from the moment it is a direct measure of friction in sheet-tool interface, i.e., is a measure of the imposition of a state of tension applied locally in the region. With respect to the tool radius is experimentally observed that the formability increases in inverse ratio of the radius. One possible explanation for this is the fact that small bands just concentrate deformation in the contact region, and its increase tends to make the process more similar to conventional conformation.

2.2. Formability ("*Spifability*") and work angle(ψ)

The work of Jeswiet *et al* (2002), as well as Park and Kim (2003) and Martins *et al*, in work “Single-point incremental forming and formability-failure diagrams” (2008), it is perceived that there is a compromise between the working angle and high formability have shown by the materials when processed it by the SPIF, and there are two experimental procedures to determine whether the material is liable to be sued by the SPIF: after a defined geometry, (a) and after some form of marking, the deformation of the blank is measured, either by direct or indirect measurement and FLC is obtained from the procurement of the principal strain, ε_1 and ε_2; (b) surfaces, with working angles progressively larger, will be obtained until the occurrence of fracture. The angle at which the rupture occurs is adopted as the maximum slope angle, ψ_{max}. The first method is usually adopted by the authors argue that the presence of necking, while the latter is adopted by those who advocate the uniform strain to failure.

Other parameters, when combined, also help explain the high formability of SPIF, such as:

- low growth rate of damage accumulation, the incremental character of the process;
- Presence of a plane strain state, in some geometries, which favors the non-appearance of necking and facilitates the uniform strain;
- tool size, inversely proportional to the formability;
- initial thickness of the plate, directly proportional to formability.

In the work of Jeswiet *et al* (2005) was a compilation of various materials which had until then been tested and their respective angles of maximum work were tabulated, as illustrated in Tab.1.

Table 1. Comparison between the maximum work angles and other parameters.

Material	ψ_{max}	FLD_0	$t_{0\ (mm)}$	Reference
AA 1050-O	67,5º	2,305	1,21	Filice *et al* (2002)
AA 6114-T4	60º	0,841	1,0	Micari *et al* (2004)
Al 3003-O	78º		2,1	Hagan e Jeswiet (2004)
”	72º		1,3	Hagan e Jeswiet (2004)
”	71º	3,0	1,21	Hagan e Jeswiet (2004)
”	67º		0,93	Hagan e Jeswiet (2004)
Al 5754-O	62º		1,02	Young e Jeswiet (2005)
Al 5182-O	63º		0,93	Young e Jeswiet (2005)
AA 6111-T4P	53º		0,93	Young e Jeswiet (2005)
DC04	65º	1,2	1,0	Hirt *et al* (2004)
DDQ	70º	2,718	1,0	Micari *et al* (2004)

It is worth mentioning that the column values FLD_0 are the points where the curves of the FLD cut the axis of ordinate - maximum deflection or ε_2 (or ε_{max}), for abscissa values - a minimum deformation, ε_{min}, or equal to zero.

2.3. Stresses and Strains in SPIF

The study of real states of deformation present in the process of incremental forming is the state of the art in this field of knowledge, since until recently the study presented by Jackson and Allwood (2009) the mechanism of deformation and predictability of the thickness along the conformation were based on the works of Avitzur and Yang (1960), and Kalpakcioglu (1961), proposed in the early sixties, who accompanied the deformation of the profiles conformed by a process similar to shear spinning, which acts pure shear in the plane containing the thickness, the deformed configuration, with the action of a plane strain state in the undeformed configuration.

Jackson and Allwood (2009), working with copper plates with an average of 3.2mm thickness, sliced lengthwise and then brazed, made the comparison between the SPIF process, the TPIF (Two Point Incremental Forming) and direct forming, with the objective to clarify the real condition of deformation along the thickness, and accept the sine law. The characteristics of the test are illustrated in Fig. 3.

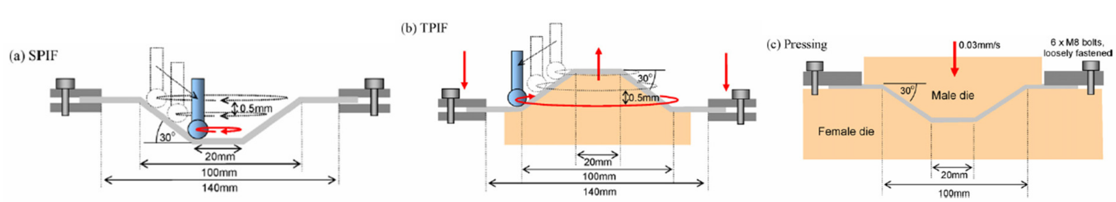

Figure 3. Comparison between SPIF, TPIF and conventional forming

These results pointed to:

- both in TPIF and SPIF the deformation is a combination of stretching and shear, which increases as the accumulation of increments, and the focus of greater magnitude in the shear deformation in the direction of action of the tool;

- the shear also occurs in the direction perpendicular to the contact with the tool, in both cases cited, and the most relevant in SPIF, which is a stacking (piling up) in the center of the proposed geometry;

- the mechanism of deformation varies inherently by setting conditions and the presence of support, if we compare the SPIF and TPIF. Even among the TPIF and shear turning, they initially have similar conditions, are different: while in TPIF the state of deformation imposed is the circumferential shear, in the shear forming, the state considered by Kalpakcioglu (1961) is the plane strain.

Regarding the validity of the sine law the results show:

- obtaining the thickness using this mathematical expression indicates low predictability compared with the experimental results, both for when the SPIF to TPIF because the mechanics of deformation allows radial displacement of material, causing this divergence;

- both the theoretical and the measured process after deformation depend on the thickness. In the work of Young and Jeswiet (2004) and Ambrogio *et al* (2005) used the plate was 1.21 mm thick, whereas in the cited work the plate was 3.2 mm thick, and the variation presented in this work is also related this fact;

- the deformation measured at the copper plate is not representative for the SPIF because stabilization of thickness after stamping certain depth, which occurs in the aluminum plates, did not occur during the testing of Jackson and Allwood (2009).

3. METHODOLOGY

Presented the advantages of using incremental forming process for the manufacture of stamped components and the assembly of pre-series, this work shows the behavior of metal components subjected to deep drawing, when it is necessary to angular variation of the wall along decrease the length and diameter. This is used for commercial aluminum, in blanks of 200 x 200mm, with initial thickness of 1.02 mm, being the increased use in the construction of structural components such as hoods, cooling towers, in other applications. To verify this technique was used SPIF, since the literature is considered to have a easier implementation. The experiment was divided into three stages, classified as follows:

I - To the capability of deep drawing, it was proposed the forming of a cone angle of steady work, the initial diameter Ø145mm and final diameter as small as possible, until reaching values close to the diameter of the tool. In Fig.4 the shape of this cone is illustrated.

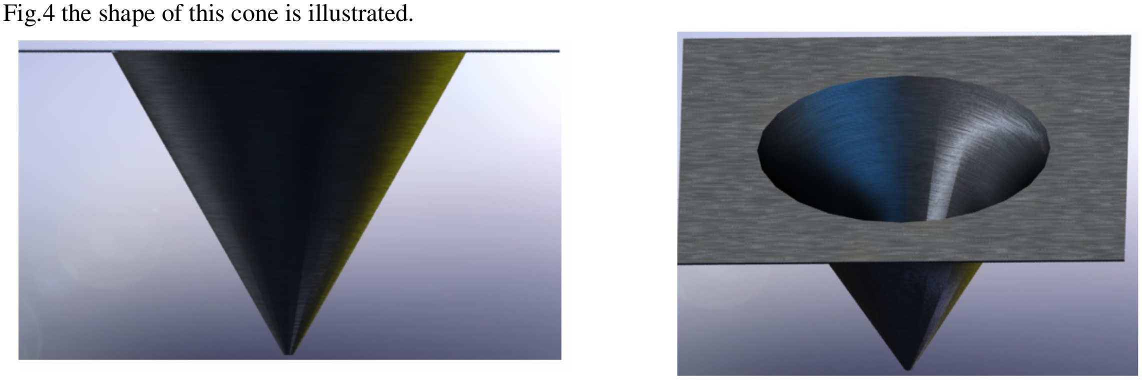

Figure 4. CAD model of the cone to be formed

II - To check the maximum work angle, we proposed the formation of a truncated cone, with decreasing diameter and increasing the angle, even if possible, arrive at the formation of a vertical wall. The CAD model of this test condition is shown in Fig. 5.

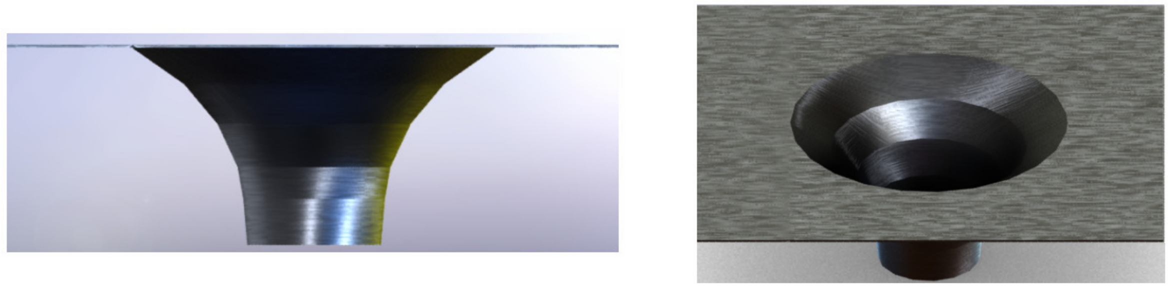

Figure 5. CAD model of the truncated cone to be formed

III - For commercial applications such as validation, it was proposed the formation of a profile that had the following characteristics: (a) variable working angle, (b) support by male, (c) change in the direction of curvature, which would require the possibility to have positive and negative working angles. In Fig. 6 this application is shown through its CAD model.

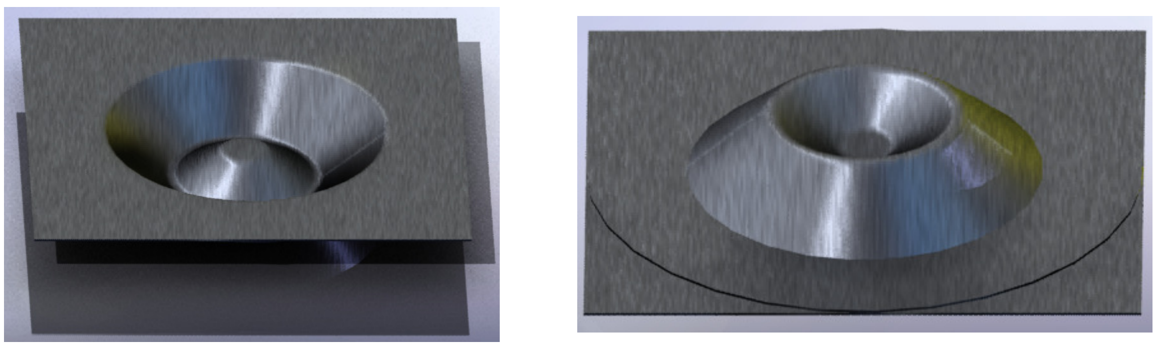

Figure 6. CAD model of the application being formed

The equipment and other devices used in this work are illustrated in Fig. 7.

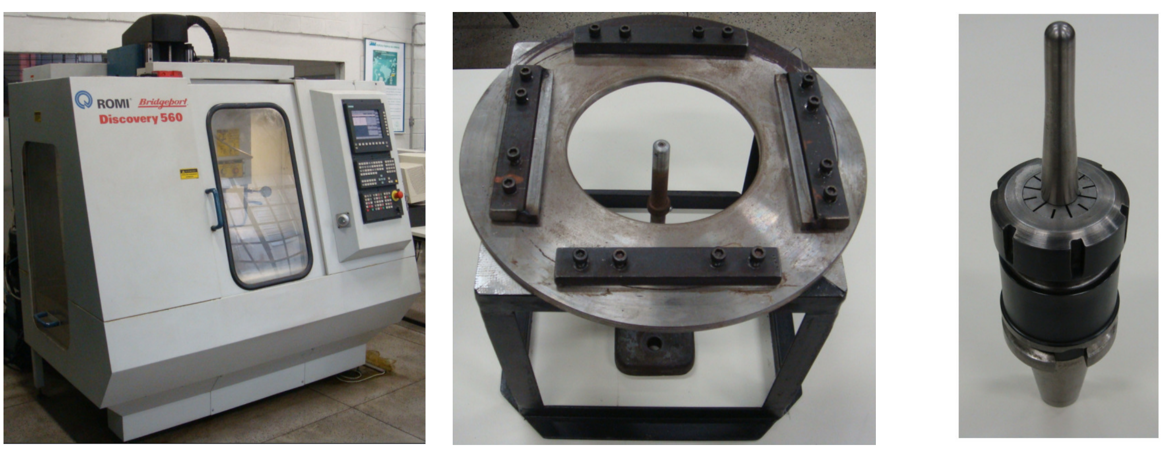

Figure 7. Equipment, device and tool

Taking as operation parameters of the machining center:
- Forward: f = 1500mm/min;
- Rotation of the bracket (trajectory velocity): n = 50 rpm;
- Rotation tool: 0 (fixed in the tool head);
- Step size: a_p = 0,1 mm.

4. RESULTS

The support was mounted on CNC table so as to provide stability to the test, i.e., rigidly fixed to ensure fidelity between the CAD model and the part fabricated.

(a) Cone with fixed work angle: the first part formed was a cone, it was possible to assess the greatest depth obtained for the material, thought process and geometry. The result can be seen in Fig. 8.

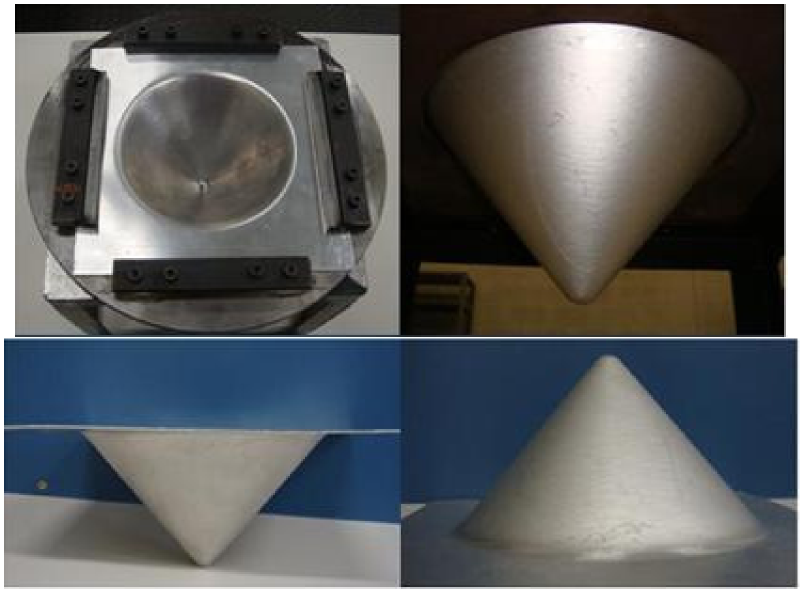

Figure 8. Cone with constant work angle, obtained by SPIF.

The dimensions obtained are illustrated in Fig. 9.

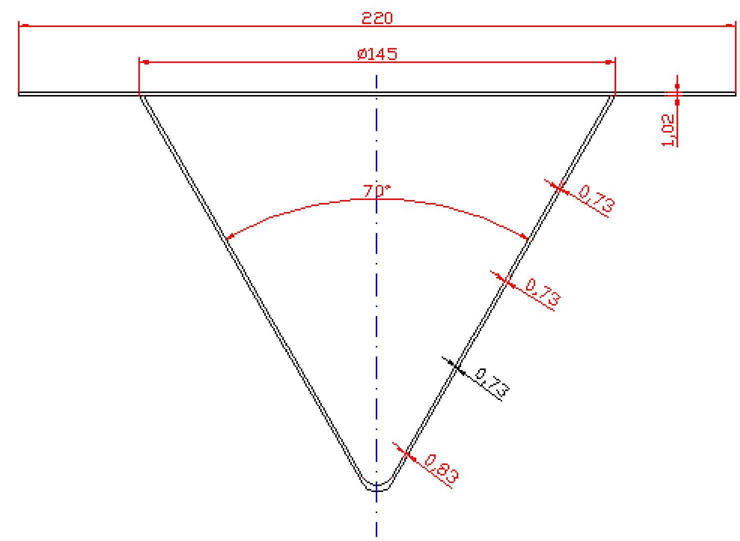

Figure 9. Dimensions obtained in the cone with constant work angle.

It is observed that could be obtained without the presence of rupture of the wall, a depth of 80mm, limited by the size of indenter. Beyond this dimension in depth, we performed a decision-wall thickness from the base to the tip of the cone.

(b) Truncated cone: Identified the forming capacity for aluminum in SPIF technique, for these operating conditions of the machining center, went the verification of performance when the angular variation of the wall, having been obtained the following results (Fig. 10).

Figure 10. Cone with constant work angle, obtained by SPIF.

The dimensional results are shown in the Fig. 11 below.

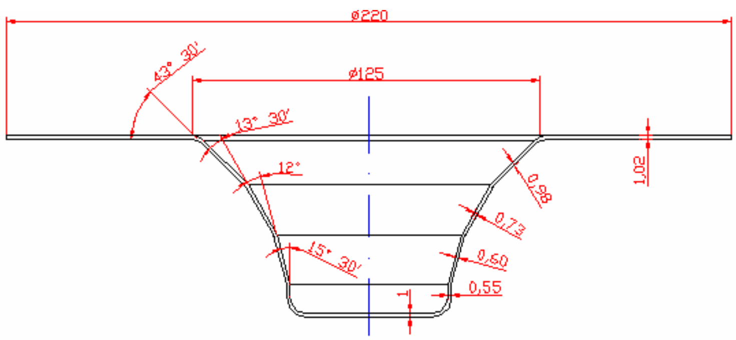

Figure 11. Dimensions obtained in the truncated cone.

(c) Application piece, with angles and forming depths: finally, the two conditions were attached, or forming with constant angle, followed by it with an angular variation of the wall and reversal in the direction of tilt, as shown in Figure 12.

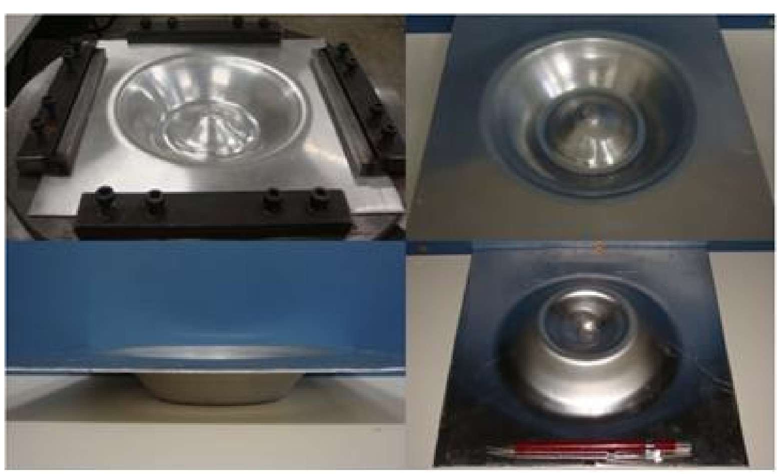

Figure 12. Application part.

The dimensional results are shown in the Fig. 13.

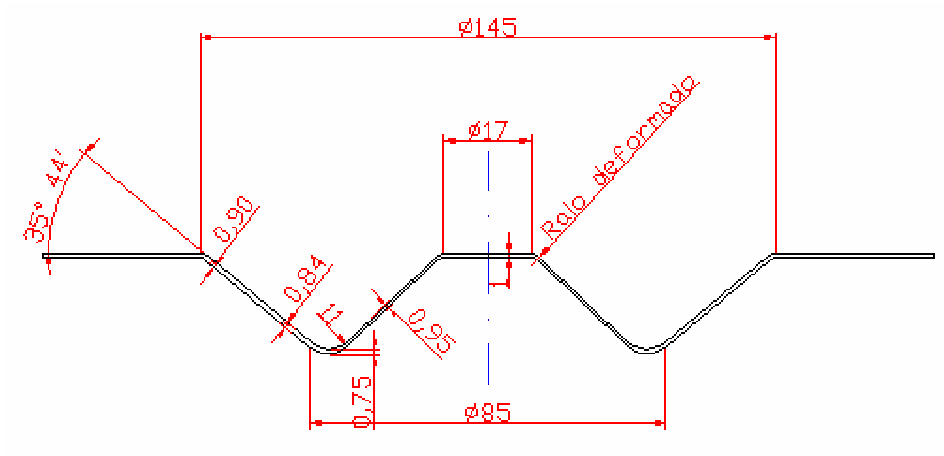

Figure 13. Dimensions obtained in the application part.

5. CONCLUSIONS

This work has as main objective to present the Incremental Forming, mainly technical SPIF as a viable alternative when it comes to obtaining parts of complex geometry, in small batches, obtained in materials of high ductility, and whose number ranges between conception and over, typical of Rapid Prototyping processes, are needed.

In these tests we can observe the correlation between the design files and the finished pieces, bringing these cases to the quantitative level, rather than just qualitatively, as a first argument may lead.

In the meantime, we can affirm that this technology, recently introduced in the industrial reality, has a strong allowance to put in the forefront of Brazilian metalworking manufacturing.

6. REFERENCES

Ambrogio, G., Filice, L., Gagliardi, F., Micari, F. Sheet thinning prediction in single point incremental forming. In: SheMet '05 International Conference on Sheet Metal,Erlangen, Germany, 2005, pp. 479–486.

Avitzur, B., Yang, C.T., Analysis of power spinning of cones. Trans. ASME, Ser. B, J. Eng. Ind. 82, 1960. pp. 231–245.

Filice, L., Fantini, L., Micari, F. Analysis of Material Formability in Incremental Forming, Annals of the CIRP, vol. 51/1/2002: 199-202.

Fratini, L., Ambrogio, G., Di Lorenzo, R., Filice, L., Micari, F. The Influence of mechanical properties of the sheet material on formability in single point incremental forming. Annals of CIRP vol 53/1/2004; p 207.

Hagan, E., Jeswiet, J. Analysis of surface roughness for parts formed by CNC incremental forming. IMECHE part B, J. of Engineering Manufacture. Vol. 218 No. B10, 2004. pp. 1307 – 1312.

Hirt, G., Ames, J., Bambach, M., Kopp, R. Forming Strategies and Process Modelling for CNC incremental Sheet Forming. Annals of CIRP vol 53/1/2004; p 203.

Jackson, K., Allwood, J., The mechanics of incremental sheet forming, Journal of Materials Processing Technology, v209, Issue 3, 1 February 2009, pp. 1158-1174.

Jeswiet, J., Hagan, E., Szekeres, A., Forming parameters for incremental forming of aluminium alloy sheet metal, IMECHE part B, Journal of Engineering Manufacture, v216, 2002, pp. 1367-1371.

Jeswiet, J., Incremental Single Point Forming, Transactions of North American Manufacturing Research Institute, vol. XXIX, 2001, pp. 75-79.

Jeswiet, J., Micari, F., Hirt, G., Bramley, A., Duflou, J., Allwood, J., Asymmetric Incremental Sheet Forming, Annals of CIRP, v54, Issue 2, 2005, pp. 130-157.

Kalpakcioglu, S., On the mechanics of shear spinning, Trans. ASME J. Eng. Ind. 83, 1961, pp. 125–130.

Martins, P.A.F., Silva, M.B., Skjoedt, M., Atkins, A. G., Bay, N., Single-point incremental forming and formability–failure diagrams, The Journal of Strain Analysis for Engineering Design, v43, 2008, pp. 15–35.

Martins, P.A.F., Silva, M.B., Skjoedt, M., Bay, N., Revisiting the fundamentals of single point incremental forming by means of membrane analysis, International Journal of Machine Tools & Manufacture, v48, 2008, pp. 73–83.

Micari, F. and Ambrogio, G. A Common shape for conducting Incremental Forming Tests. 1st Incremental Forming Workshop, University of Saarbrucken, 9 June 2004. On Cdrom.

Park, J-J., Kim, Y-H., Fundamental studies on the incremental sheet metal forming technique, Journal of Materials Processing Technology, v140, 2003, pp. 447-453.

Park, J-J., Shim, M-S., The formability of aluminum sheet in incremental forming, Journal of Materials Processing Technology, v113, 2001, pp. 654-658.

Young, D., Jeswiet, J. Forming Limit Diagrams for Single Point Incremental Forming of Aluminum Sheet. IMECHE part B, J. of Engineering Manufacture, vol. 219 part B 2005. pp 1 – 6.

Young, D., Jeswiet, J., Wall thickness variations in single-point incremental forming. Journal of Eng. Manufact. Part B 218, 2004, pp. 1453–1459.

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