UNIVERSIDAD DE LAS AMÉRICAS-PUEBLA

ESCUELA DE INGENIERÍA

DEPARTAMENTO DE INGENIERIA INDUSTRIAL, MECÁNICA Y LOGÍSTICA

“Comparison of two sheet metal forming processes: Conventional Stamping vs. Incremental Sheet Forming”

TESIS QUE, PARA COMPLETAR LOS REQUISITOS DEL PROGRAMA DE HONORES PRESENTA

Arturo Javier Belmont Gálvez

COMO REQUISITO PARCIAL PARA OBTENER EL TÍTULO DE LICENCIADO EN INGENIERIA MECÁNICA

Santa Catarina Mártir, Puebla **Primavera 2018**

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12 de mayo de 2018

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Tesis presentada por Arturo Javier Belmont Gálvez como requisito parcial para obtener el título de *Licenciado en Ingeniería Mecánica.*

Aceptada por el *Departamento de Ingeniería Industrial, Mecánica y de Logística.*

Director de la tesis y vocal	Presidente del jurado
Dr. Rogelio Pérez Santiago	Dr. Jorge Arturo Yescas Hernández
(Nombre y firma)	(Nombre y firma)
Secretario del Jurado	Director Académico
(Nombre y firma)	(Nombre y firma)
M. Paola Torres Madrid	Dra. Carmen Xóchitl Flores Mendoza
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Como ingeniero de profesión, me comprometo a:

- Proteger la salud, seguridad y bienestar del público.
- Desempeñar servicios sólo en áreas de mi competencia.
- Conducirme en forma honorable, responsable, ética y legalmente; a fin de mejorar el honor, reputación y utilidad de mi profesión.

Con respeto y honradez, hago el presente juramento.

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(Nombre y Firma)

Santa Catarina Mártir, Puebla; a 12 **de** mayo **de** 2018

CARTA DE APROBACIÓN DEL DIRECTOR PARA LA DEFENSA

El director de la tesis Dr. Rogelio Pérez Santiago, considera que el trabajo reúne requisitos mínimos y la estructura académica básica para ser presentado y defendido ante un jurado.

Autorizado el día 04 del mes de mayo de 2018.

Dr. Rogelio Pérez Santiago

Nombre y firma

AGRADECIMIENTOS

Para mí el día de hoy significa el término de una etapa, quizá de las mejores de mi vida, a la cual llego a la meta con las manos llenas, la mochila a tope y orgulloso de estar aquí, desde pequeño siempre fui un niño intenso, bueno creo que lo sigo siendo, y sobre todo aferrado a las cosas que quiero, esta tesis es una prueba de ello y representa más allá de la culminación de mi carrera, un enorme agradecimiento a mis padres quienes lo dieron todo por darme siempre lo mejor.

El graduarme como ingeniero mecánico con honores y hacer esta tesis por gusto y mérito propio requiere de ambición, ganas, dedicación y disciplina, cada una de estas aptitudes las aprendí de mi papá que no hubo un sólo día que no me motivará a ir por más y nunca conformarme con nada, a que haciendo las cosas bien, siempre se abrirá una puerta y habrá una recompensa, aquí está tu ingenierito, felicidades papá lo lograste.

Y finalmente el apoyo incondicional de mi hermana y mi cuñado que me han enseñado que la familia es primero y que por ella lo damos todo.

Dado que haber llegado hasta aquí no fue únicamente de ellos, es justo dedicar este trabajo a quienes donaron el resto, empezando por mi familia, profesores y amigos. Gracias a todos por acompañarme en este día y les prometo que habrá más días como hoy.

Deséalo tanto

Hasta que el universo diga:

"Toma, Toma y deja de joder"

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RESUMEN

Los procesos de deformación de lámina son muy importantes en la industria actualmente, es necesario tener un vasto conocimiento del comportamiento de la misma para poder así seleccionar la manera adecuada de deformarla. En este trabajo dos procesos de deformación de lámina van a ser abordados desde cero hasta tener un producto final y evaluar sus características.

Después de revisar el estado del arte, queda claro que, aunque muchas comparaciones y estudios acerca de conformado incremental y estampado de lámina se han realizado, ningún autor ha manufacturado la misma pieza utilizando ambos procesos, por ello esta investigación cubre un nicho importante dentro de la literatura, ya que explica paso a paso la metodología, el equipo necesario y el proceso a seguir para poder realizar una pieza estampada con dados suaves y una pieza por conformado incremental de lámina.

Los resultados experimentales indicaron que el estampado convencional tiene un costo más elevado ya que se requiere de la fabricación de dados suaves para el desarrollo de esta, sin embargo, ya teniendo los herramentales, la producción de piezas estampadas es mucho más rápida ya que en cuestión de segundos se puede obtener la pieza. En cuanto al conformado incremental, es necesario decir que la deformación que ocurre durante este proceso es 3 o 4 veces mayor a la que ocurre en estampado, por lo tanto, la lámina presenta un adelgazamiento mayor, dando en consecuencia que esta tenga una resistencia más baja.

CHAPTER I - INTRODUCTION

1.1 Context of the Research

1.1.1 Manufacturing processes

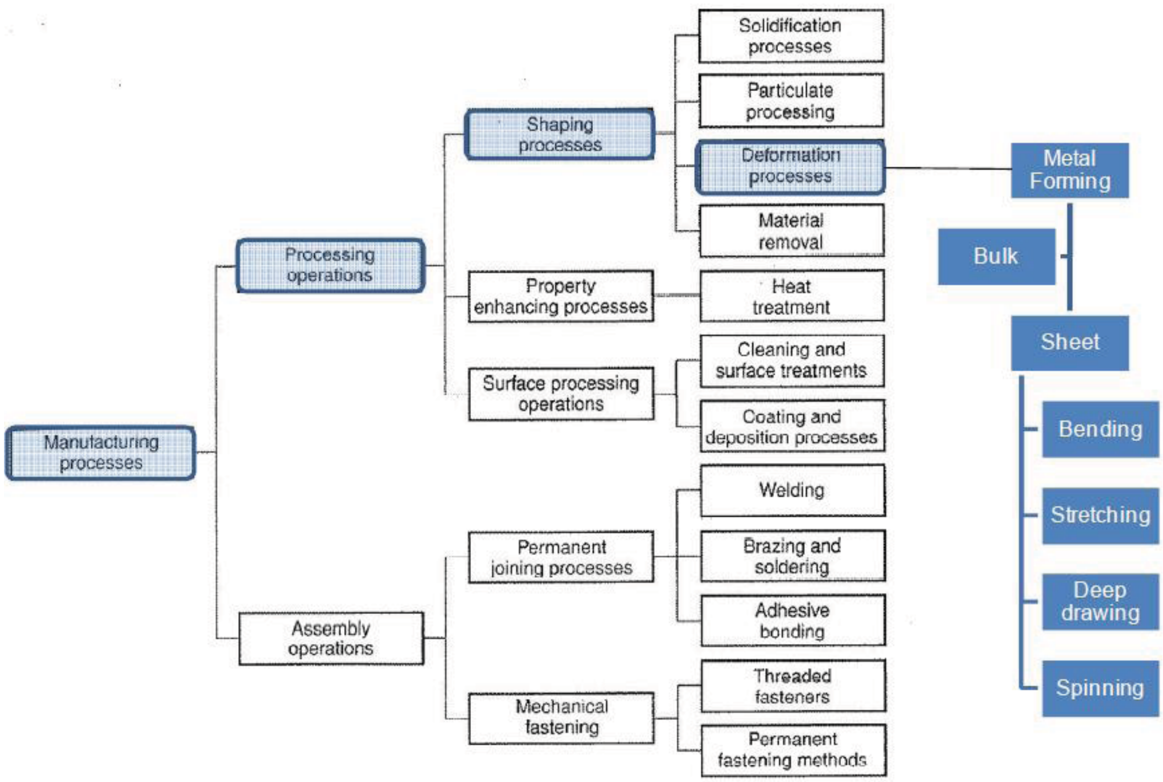


Figure 1. 1 Manufacturing classification according to Groover

According to Groover, manufacturing processes are divided in processing and assembly operations, both following different procedures.

Processing operations tend to transform the raw material to get the final product and on the other hand, assembly operations tend to join into an assembly two or more parts into a final product.

From the vast family processing operations, this thesis is focused in shaping processes, more accurately deformation processes; in which the final product is reached by the application of forces beyond the yield limit of the material. These processes can be divided in bulk and sheet variants in which the difference lies in the surface/volume ratio typically from sheet metal parts.

Bulking processes generally distinguish themselves by their initial form which is rather a bulk than sheet, some common examples are rolling, forging and extrusion among others.

As it will be exposed, the processes studied in this document, Incremental Sheet Forming and Conventional Stamping belong to the sheet processes. Each of them having their advantages, both relying in the deformation applied by the tool in order to get a final product.

1.1.2 Conventional Stamping

During conventional stamping, a hollow part is obtained by forcing a flat metal sheet into a die using a punch. The blank is fixed by a holder while the central portion of the sheet is drawn into a die opening with a punch to mold the metal into the final shape without causing wrinkles or splits in the deformed part.

According to Lange, the thickness is assumed to be constant and this process is capable of forming beverage cans, sinks, cooking pots, ammunition shell containers, pressure vessels, and auto body panels parts. Deep drawing involves the use of presses having a double action for hold-down force and punch force.

The most critical region of a deep-drawn part is the flange, which is under circumferential compressive and radial tension stresses. To prevent wrinkling and to control the process, a blank holder (also referred to as the draw pad or binder) is used (Figure 1.2).

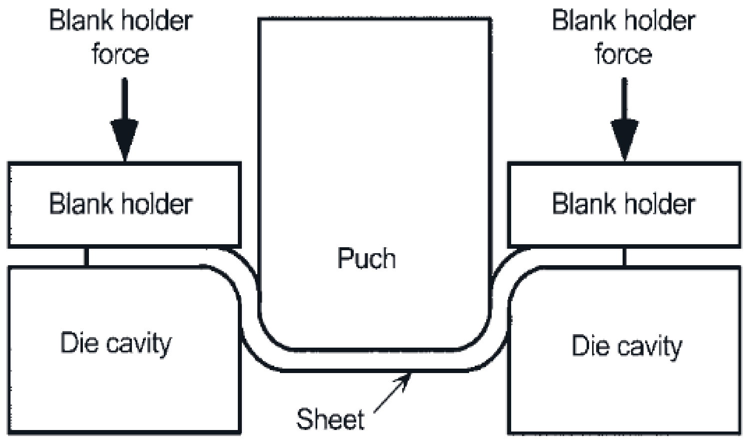


Figure 1. 2 Schematic of the deep drawing process (Tekkaya).

The blanksholder's purpose is to apply a blank holder force (BHF) onto the cup flange to avoid wrinkling, this usually happens when a BHF is not used during the process or insufficient force is applied, as shown in (Fig. 1.3).

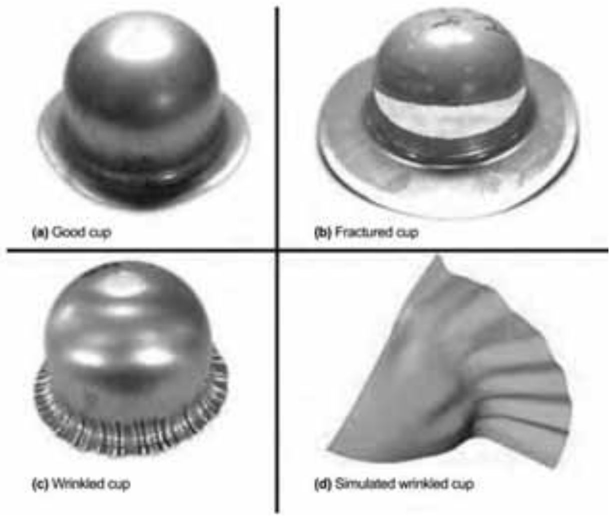


Figure 1. 3 Experimental of deep drawn cups (Tekkaya).

Other use of the blankholder is to prevent the material to flow into the die by the increase of friction at the flange which causes radial tension stresses in this critical zone, on the other hand, if too much BHF is applied it may end in the fracture of the part before the desired depth is achieved, therefore the BHF is so important in this process.

Lange determined that the load required to form the part is indirectly applied by the punch on the bottom of the part. The part wall transmits the load to the deforming zones of the blank, and as a result, the cup wall is under tensile stresses that may lead to fracture, usually just above the punch corner.

In conventional stamping sequential forming steps are developed during two or more stations in which the strip of the material flows through the die. It is possible to have one or more idle stations in which no deformation is performed.

These stages obviously have their purpose which is to help the strip travel or to simplify the die design. At each station, the material is deformed being able to produce one or more parts with each stroke. Conventional stamping is mainly considered for large production volumes due to its short cycle and easy operation.

For this process, the number of forming stations and tool geometry of each one must be defined, this means the punch and die diameter, punch corner and die corner radius, (Fig 1.4) then for each station the draw depth and the blank holder force should be calculated. These are the main challenges when designing a complete stamping station to satisfy all the specifications of the product concerning overall dimensions, tolerances, residual stresses and finishing surfaces.

This type of processes usually involves prior knowledge based on experience in similar production parts, also this methodology requires vast resources and a considerable design time.

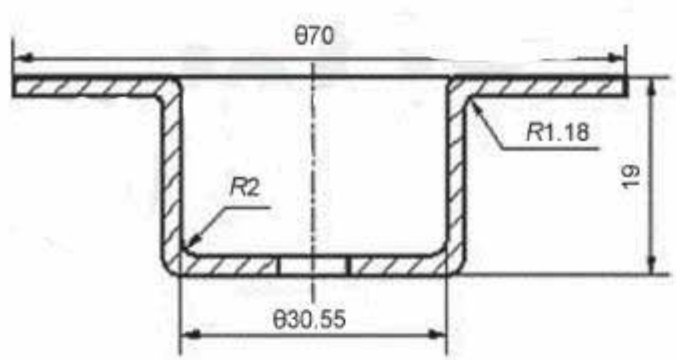


Figure 1. 4 Dimensions of an existing automotive part (Tekkaya).

1.1.3 Incremental Sheet Forming

As Bambach explains, deep drawing is a very cost-effective and well-established process for the mass production of sheet metal components. However, due to the high costs and prolonged manufacturing time for die manufacturing it is not suitable for small batch productions in a short time period. To achieve a profitable short-term production and prototyping of sheet metal parts, incremental sheet forming processes based on computer numerical-controlled (CNC) machines have been developed.

The principle of this technique is to generate a tool path in order to process the geometry by using a generic tool designed for this process. The forming tool follows the path previously programmed and imposes a localized plastic deformation.

These sequential plastic deformations add up to create the final shape of the deformed part. Incremental sheet forming (ISF) was first de-scribed in 1967 in a patent made by Leszak, at this time CNC manufacturing was not that reachable as today, nevertheless, during the early 1990s, this process was investigated and developed by an ever-growing number of research teams and companies. Some examples manufactured using ISF are shown below in Fig. 1.5

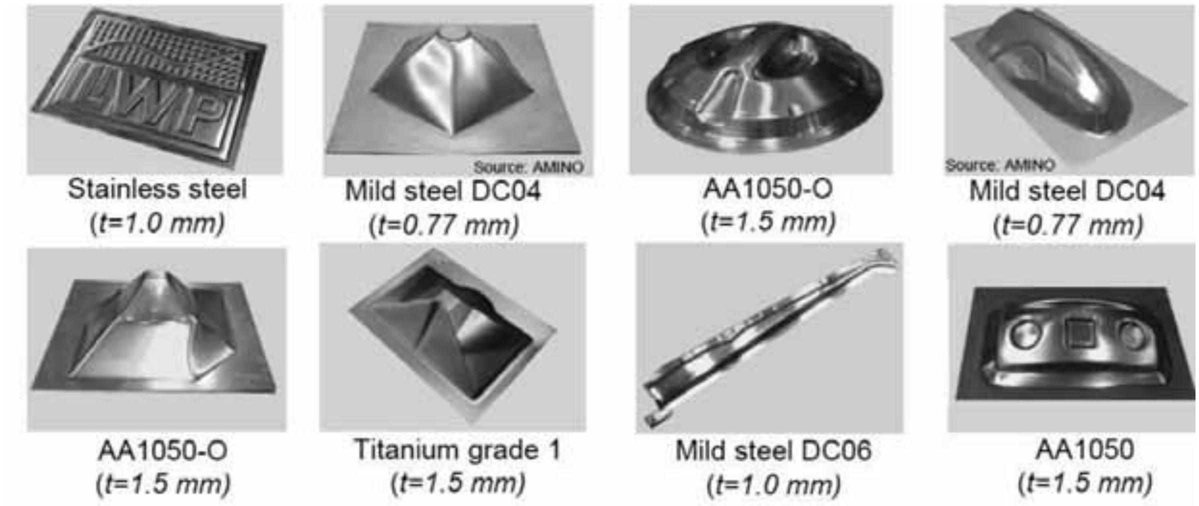


Figure 1. 5 Various parts manufactured by incremental sheet forming (Altan).

Jeswiet defined ISF as a process which:

- Has a solid, small-sized forming tool
- Does not have large, dedicated dies
- Has a forming tool that is in continuous contact with sheet metal
- Has a tool that moves under control, in three-dimensional space
- Can produce symmetric as well as asymmetric sheet metal shapes

ISF is commonly divided in 3 different processes known as:

- Single Point Incremental Forming (SPIF)
- Two Point Incremental Forming (TPIF)
- Kinematic Incremental Sheet Forming (KISF)

➢ Single Point Incremental Forming.

This process is distinguished by the use of a forming tool which works by deforming the metal sheet with a single point contact. The blank is clamped to a holder that remains at the same height as shown in Figure 1.6

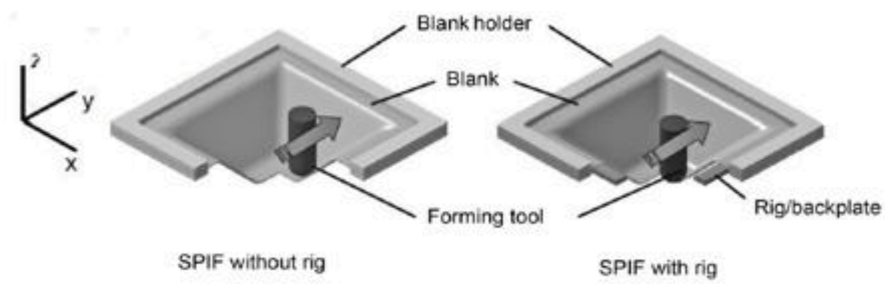


Figure 1. 6 Single point incremental sheet forming (Altan).

➢ Two Point Incremental Sheet forming

For this process, a partial holding die is required to expand the blank and get the desired geometry. This technique is suitable for geometries with a defined curvature and those with no further deformation stages for which the holding die is designed. This process follows the same procedure as SPIF, the sheet is clamped to the holder and deformed by the CNC forming tool, which travels in a vertical direction contrasting SPIF, the sheet acquires its final shape from the outside by using the die holder. (Fig.1.7)

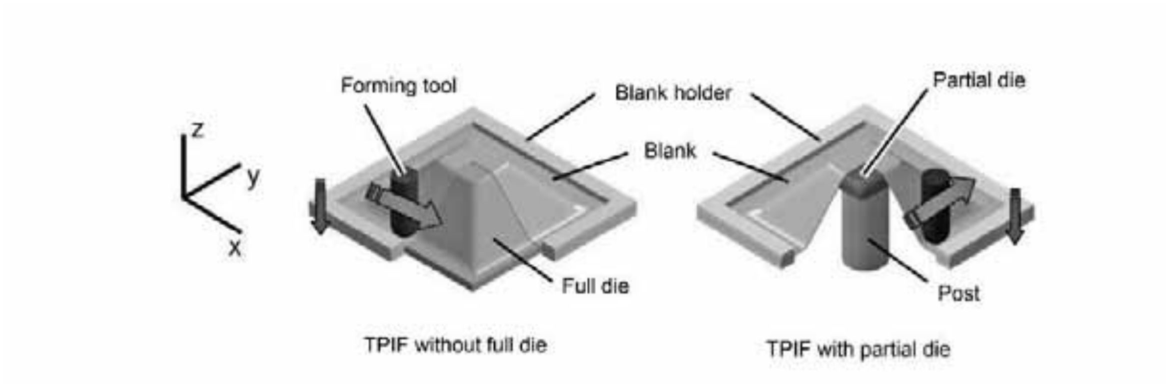


Figure 1. 7 TPIF (Altan).

- Kinematic Incremental Sheet Forming

In this procedure two forming tools are used, opposite to each other separated only by the blank, both tools work simultaneously and offer additional flexibility over SPIF technique.

One disadvantage of this technique is the synchronization of the tool paths and the precision required in the process.it is usually performed by two robots to avoid desynchronization. (Fig.1.8)

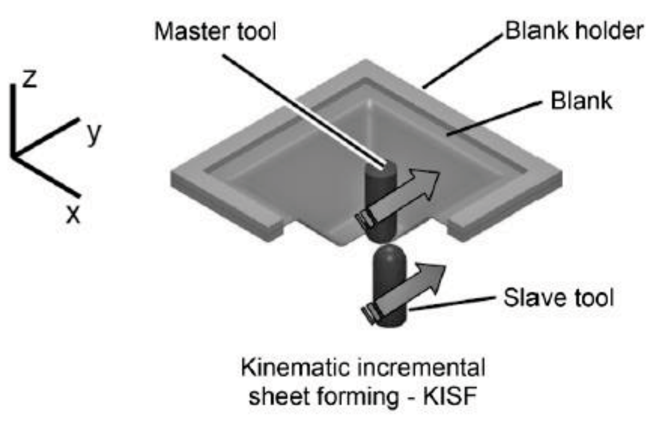


Figure 1. 8 Kinematic incremental sheet forming using two forming tools (Altan).

1.2 Thesis topic

A detailed description of both, ISF and conventional stamping is left for the next chapter. In this point the discussion will focus on a distinctive feature pointed out by several researchers like Jeswiet, Yanle Li and McAnulty who all claim that ISF is justified because it is a dieless process that can be used for small batch productions and rapid prototypes only available with the use of a CNC milling machine and CAD/CAM software.

If adapted CNC machinery will be used to perform ISF with the CAD/CAM software, would not be also possible to use them to manufacture soft dies intended to produce the same part with stamping? Based on the prototypes we have made, the clamping device used for ISF can also be adapted for conventional stamping.

Indeed, a certain fact should be questioned; If using SPIF, based on an adapted CNC milling machine, is a better (from a quality standpoint), quicker and cheaper process than conventional stamping.

Despite valuable knowledge available in the literature, important gaps regarding the previous questions remain: the belief that one process is better than the other has not been evaluated in a back to back comparison; manufacturing the same part using SPIF and conventional stamping.

This need defined the main research line of the present work, the evaluation of two different processes for manufacturing the same part.

1.3 Research Questions

This study involved stainless steel sheet of 0.5mm thickness. Additionally, the selection of geometry is defined as a rectangular pyramid (simple geometry), where the main objective will be to answer this research questions.

I. Is it true that conventional stamping processes are only viable when manufacturing large productions?

II. Can conventional stamping be manufactured at relatively the same costs and time than SPIF?

III. Which process allows to have better resistance, precision, and repeatability itself?

1.4 Outline of the Document

Aiming for accurate responses, this study means to clarify which process is really the best option, when there is a need to prototype a sheet metal component from scratch, without taking in account the common belief that one is only for small batch rapid prototyping and the other is used for volume production. Accordingly, chapter 2 begins with a review of the literature regarding SPIF processes and SPIF compared with other processes.

Chapter 3 presents the details of the experimental methodology used in this study, during this part, the parameters used were selected to allow the comparison between the two processes and also the cost production was retrieved and explained.

Chapter 4 details the experimental results of both processes and reveals the tests conducted in each pyramid to measure deformation, resistance, precision and repeatability.

Finally, Chapter 5 concludes the back to back comparison of both experimental processes and determines which is better in the 5 tests that were evaluated.

CHAPTER II -LITERATURE REVIEW

2.1 Introduction

As explained earlier, one important objective of this work is generating reliable information of which process is a better option. Accordingly, this section starts with a brief description of the processes, its main variants and the related equipment, before comprehensively regarding the state of art of the comparison between the two processes, Single Point Incremental Sheet Forming and Conventional Stamping. In alignment with the research approach, experimental and analytical comparison studies will be covered.

2.2 The Incremental Sheet Forming Process

As explained earlier in chapter 1, according to Jeswiet, incremental Sheet forming acquired great notoriety due to the possibilities of manufacturing small batch production quantities with very short turnaround times from design to manufacture, also Schmoeckel predicted in the early 90´s that with the increase automation metal forming equipment would become more flexible, and within 10 years, this happened. This process was patented by Leszak before it was technically feasible until having the facility of a three-axis CNC mill and the basic elements required perform ISF.

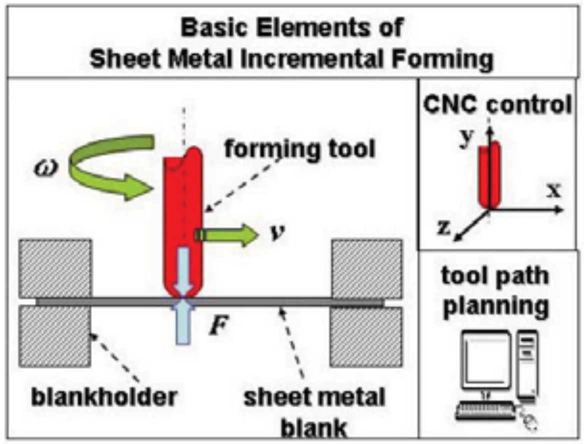


Figure 2. 1 The basic elements needed for asymmetric Incremental Sheet Forming.(Tekkaya)

Incremental sheet forming was researched and performed by Jeswiet and Leach with the use of a CNC three-axis mill and CAD/CAM software to fabricate complex parts.

2.2.1 Formability

Also, Incremental sheet forming has higher formability limits than other sheet metal forming processes including stamping, according to McAnulty, but to take advantage of this high formability, it is necessary to understand how to maximize the limits through manipulation of parameters regarding material thickness, tool diameter, tool shape and type, step down, feed rate, spindle speed and rotation direction.

In many research papers formability is most commonly quantified by finding the maximum wall angle to which the material can be formed before fracture, with respect to the horizontal plane. Typically, a simple shape, such as a cone or pyramid, is used to determine this maximum wall angle. Many experiments can be formed, each one with a steeper wall angle than the previous, until the wall fractures.

Material	ϕ_{max}	FLD_o	t_o , mm	
AA 1050-O	67.5°	2.305	1.21	Filice [31]
AA 6114–T4	60°	0.841	1.0	Micari [63]
Al 3003 – O	78.1°		2.1	Jeswiet [59]
Al 3003 – O	72.1°		1.3	Jeswiet [59]
Al 3003 – O	71°	3.0	1.21	Jeswiet [59]
Al 3003 – O	67°		0.93	Jeswiet [59]
Al 5754 – O	62°		1.02	Jeswiet [59]
Al 5182 – O	63°		0.93	Jeswiet [59]
AA 6111–T4P	53°		0.93	Jeswiet [59]
DC04, mild steel	65°	1.2	1.0	Hirt [65]
DDQ	70°	2.718	1.0	Micari [63]
HSS	65°	1.924	1.0	Micari [63]
Copper	65°	1.808	1.0	Micari [63]
Brass	40°	0.701	1.0	Micari [63]

Table 2. 1 A list of materials with initial thickness and maximum draw angles. (Jeswiet 2005)

2.2.2 Geometry

The shape of the incrementally formed part affects the strains and therefore the formability of the material. The geometry is an aspect which is not covered in this research due to the complexity of analyzing the many different shapes and dimensions used in this method.

2.2.3 Experimental parameters

Since the process was first developed, several modifications have been made to the basic SPIF, for example different heating alternatives for the workpiece have been explored.

Duflou et al. in 2007 used a laser to improve the maximum wall angle of TiAl6V4 sheets by more than 20°C. The same Titanium alloy was heated up to 400°C with band heaters installed in the blank holder and an improvement in formability was observed.

The use of electric current through the tool and the sheet has been explored in recent years, also applied to TiAl6V4 and other materials such as AA6061-T6 with resulting formability improvements. As this research studies process parameters for basic SPIF, parameters relevant to hot SPIF and electric SPIF are not examined.

Hussain et al. examined the influence of the tool radius (R) to thickness (t) ratio (R : t) on failure, which can be said to preclude formability. The material was tested at two thicknesses, 0.7 and 2.6 mm.

They conclude that optimization of R : t ratio is needed to maximize the success of parts. PVC (Polyvinyl chloride) was tested in 5 papers and the majority concluded that an increase in sheet thickness improved the formability of the material. On the other hand, Franzen et al. found a slight trend towards increased formability with the thinner sheet.

- Tool diameter

McAnulty et al., examined 23 papers and concluded that many other parameters affect directly the formability of the part, meaning formability is directly affected by the other parameters. Table 2.2 shows the details of each paper, with additional information about material type, thickness, and number of test repeats.

Considering the consulted data on tool diameter, there is no clear fact about the effect this parameter has on formability. A clear explanation cannot be implied if the results are grouped by material type (e.g. polymers, aluminum alloys, other materials). However, the 6 papers in the Optimize category provide strong evidence that other parameters should be considered as they test a large number of different tools, over a wide range of materials and thicknesses.

Papers	Diameter [mm]	Material	Test repeats
Conclusion: **Decrease** *tool diameter to increase formability*			
Ham, 2006 [30]	4.7625, 12.7	AA3003-O	N/A
Ham, 2007 [38]	9.525, 12.7, 19.05	AA6451, AA5182, AA5754	N/A
Hussain, 2008 [42]	8, 12, 16	Commercially Pure Ti	2
Martins, 2009 [31]	10, 15	POM, PE, PA, PVC, PC	N/A
Petek, 2009 [43]	10, 16	DC05	3
Durante, 2011 [14]	5, 10, 15	AA7075-O	N/A
Silva, 2011 [44]	8, 12, 20, 30, 50	AA1050-H111	2
Marques, 2012 [34]	8, 10, 12	PET, PA, PVC, PC	N/A
Shanmuganatan, 2013 [35]	2.5, 5, 10	AA3003-O	N/A
Centeno, 2014 [15]	6, 10, 20	SS304	3
Conclusion: **Optimise** *tool diameter to increase formability*			
Kim, 2002 [12]	5, 10, 15	AA1050-O	N/A
Ambrogio, 2006 [45]	10, 12, 18, 20	AA1050-O	N/A
Ziran, 2010 [11]	4, 6, 10	AA3003-O	N/A
Hussain, 2010 [29]	6, 8, 11, 14, 16	AA2024-O	1
Hussain, 2013 [39]	7, 10.24, 13.5, 20	AA2024-O	2
Al-Ghamdi, 2014 [46]	2.2, 3.6, 4.4, 5.4, 6.6, 7.8	AA2024-O, AA2024-T6, AA1060-O, AA1060-H24, AA5083-O, Steel DS, Cu H59	2
Conclusion: **Increase** *tool diameter to increase formability*			
Strano, 2005 [47]	2.2, 3, 6.4	AA1050-O	N/A
Le, 2008 [4]	6, 12	PP	3
Franzen, 2009 [40]	10, 15	PVC	N/A
Silva, 2010 [33]	10, 15	PVC	N/A
Li, 2014 [48]	10, 20, 24.5, 30	AA7075-O	N/A
Golabi, 2014 [36]	6, 14	SS304	N/A
Bagudanch, 2015 [37]	6, 10	PVC	3

Table 2. 2 Tool diameter Summary of papers (McNaulty and Jeswiet, 2016)

For example, Hussain et al. varied both thickness and tool diameter, and Al-Ghamdi and Hussain tested 7 different materials. This implies that material thickness and material type should be considered when choosing a tool.

Conventional tools in SPIF have been purely hemispherical and it is only within the last decade that research has been exploring the applications of tools with non-conventional cross sections. Ziran et al. compared flat and hemispherical tools, and found that formability was increased when using one type of flat ended tool, but decreased for other types. This area should be tested for new researches with flat and other shaped tools, having an effect not only on formability but also surface roughness and forces applied. This could help the user to know which tool to use in a particular application.

- Step down

According to McAnulty et al., who found 18 papers that varied step down to determine the effect on formability. Most papers (13) concluded that decreasing the step down improves the forming limits of the material, and 7 papers conducted tests which presented opposite results. Fig. 2.2.

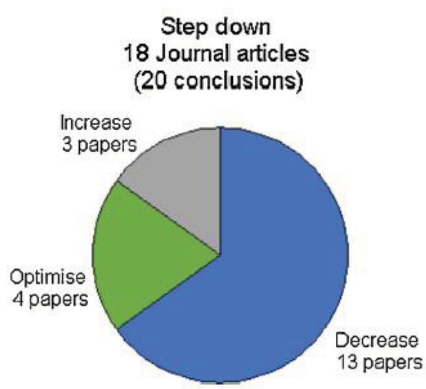


Figure 2. 2 Step down conclusions (McAnulty,T. et al., 2016)

So, it can be concluded that decreasing the step down will increase the formability, but will also affect forming time. It may be necessary in some situations to optimize process depending in each part.

- Feed rate

McAnulty et al., examined total of 7 papers that varied the feed rate of the tool and observed the effect on formability (Fig.2.3). No clear conclusion could be reached, but the most common result was that decreased feed rate increased the formability.

Hussain et al. showed that feed rate behaved differently on AA2024 whether it is annealed or has been aged. Specifically, for the aged sheet formed better at a slower feed rate, however no effect was noted with the annealed sheet. Each of these conclusions are separated in the pie chart below.

Ambrogio and Gagliardi measured the process temperature of SPIF at high speeds using a lathe. They found an optimum value of feed rate that maximized the generated temperature and increased the formability of the material. The upper and lower limits of the tests were quantitatively specified, but not the implied midpoint. It was concluded that the heating of the sheet at lower feed rates increased formability.

Feed rate: summary of papers.

Papers	Material	Feed rate [mm/min]	Test repeats
Conclusion: **Increase** *feed rate to increase formability*			
Bagudanch.	PVC	1500, 3000	3
Conclusion: **Optimise** *feed rate to increase formability*			
Ambrogio, 2015	AA5754, Ti6Al4V	5000–500,000	N/A
Conclusion: **Decrease** *feed rate to increase formability*			
Ham, 2006	AA3003-O	1270, 2540	N/A
Le, 2008	PP	1000, 3000	3
Hussain, 2008	Titanium	1200, 2600, 4000	2
Hussain, 2010	AA2024-T4	600, 1200, 2100, 4500	1
Conclusion: **No significant effect** *of feed rate on formability*			
Hussain 2010	AA2024-O	373, 1200, 2437, 3674, 4500	1
Golabi, 2014	S304	600, 1200	N/A

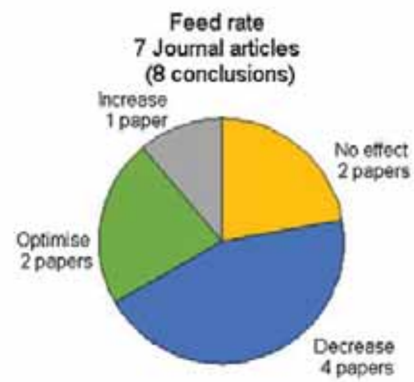


Figure 2. 3 Feed rate summary of papers. (McAnulty et al.,2016)

On the other hand, the only paper which found increasing feed rate to cause an increase in formability was with PVC, also interesting experiments can be made with high as 5000 or 10,000 mm/min. At such high feeds, there may be detrimental effects to formability or surface roughness which would result in a revision of the conclusion to ‘Optimize’.

It clear that influence of feed rate depends on the material being formed. In addition to step down, feed rate impacts the process time. Therefore, an optimization should be made if a modification between forming time and increased formability was necessary, Prior experience in the effect of feed rate on the material being formed would be required, as well as the relative increase in formability per decrease in feed rate.

- Spindle speed

McAnulty et al., reviewed 8 journal articles in which the effect of spindle speed on formability was tested, listed in Fig 2.4. In which most of them concluded that an increase in spindle speed causes an increase in formability.

Papers	Material	Spindle speed [rpm]	Test repeats
Conclusion: **Increase** *spindle speed to increase formability*			
Ham, 2006	AA3003-O	100, 600	N/A
Le, 2008	PP	200, 700	3
Xu, 2013	AA5052-H32	0, 250, 500, 750, 1000, 2000, 3000, 4000, 5000, 6000, 7000	N/A
Buffa, 2013	AA1050-O, AA1050-H24, AA6082-T6	100, 2000, 4000, 6000, 8000, 10,000	N/A
Bagudanch, 2015	PVC	1000, 2000 [a]	3
Conclusion: **Optimise** *spindle speed to increase formability*			
Obikawa, 2009	Al foil, 0.05 mm	0, 5000, 10,000, 20,000	N/A
	Al foil, 0.012 mm	0, 2500, 5000, 10,000, 20,000, 25,000	N/A
Davarpanah, 2015	PVC, PLA	0, 1250, 5000, 7000	4
Conclusion: **No effect** *of spindle speed on formability*			
Petek, 2009	DC05	0, 40 [a]	3

[a] Free rotation of the tool was also tested.

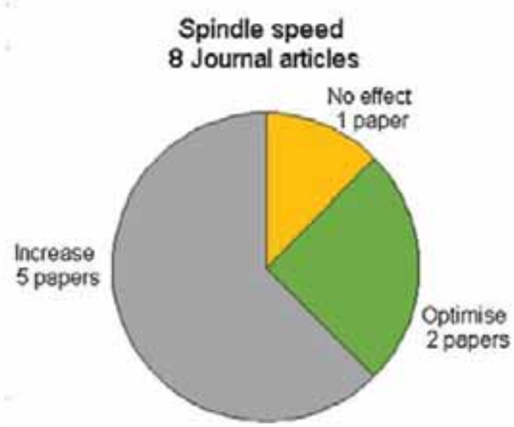


Figure 2. 4 Spindle speed conclusions (McAnulty,T. et al.,2016)

Buffa et al. tested three different materials over a large range of spindle speeds. The chosen materials are typically hard to form at room temperature, but formability improved by approximately 10 degrees over the range. The increase is attributed to changes in the crystal structure and grain growth as the high speeds cause heating in the sheet.

As it can be concluded, all parameters have varying effects among all the experiments made, this can only tell us that each parameter is independent and therefore do not have consistent effects across all situations. For this research we will keep the same parameters during the experiments and for both processes the material characteristics and temperature will remain the same as the geometry to be formed in order to get clear conclusions of the formability behavior of the material, surface roughness and forming time.

2.3 The Incremental Sheet Forming Equipment

In order to perform this process, many adaptations can be made to any CNC Milling machine, also there are robots adapted for this process and machines specially built for ISF.

2.3.1 Adapted CNC milling Machines

Almost any 3-axis milling machine is suitable for the ISF process. The main advantage of this type of machine is having the possibility to form sheet metal through moderate investment in the sheet clamping system and forming tools.

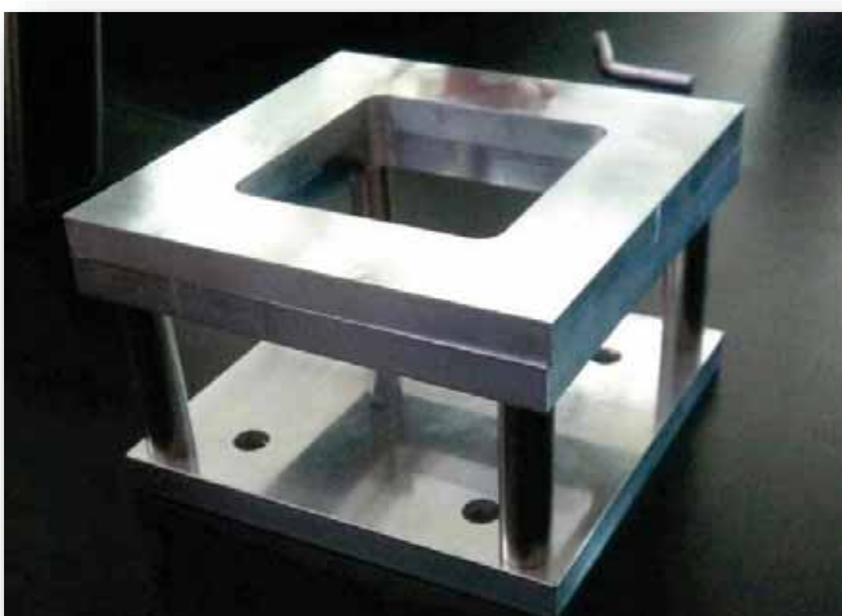


Figure 2. 5 Clamping system used for the research

As indicated by Pérez-Santiago most researchers, including himself (Spain), Jeswiet (Canada), Duflou (Belgium), Ceretti (Italy), and Hussain (China) among others, have utilized adapted CNC milling machines for their experiments.

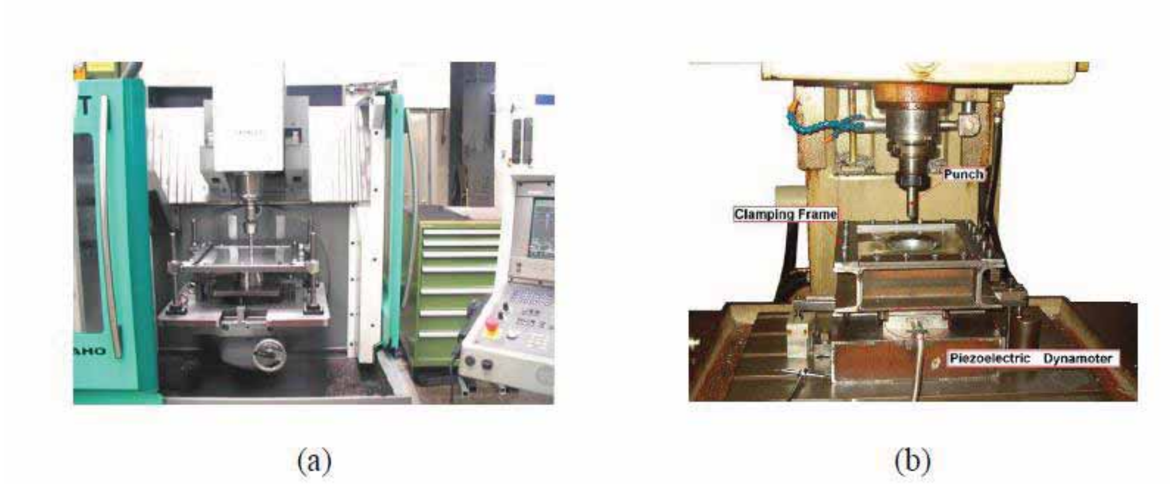


Figure 2. 6 CNC machine centers adapted for ISF process by (a), Jadhav (2005 TPIF) and (b) , Amborgio et al.(2006, SPIF)

This option is the most common one and is the way this research will perform the experiments regarding to SPIF due to the facilities of our laboratory and the prior knowledge in this kind of process.

2.3.2 Robots adapted for the ISF Process

The second possibility is the adaptation of a robot. Similarly, to the CNC adaptation, this robot must also be modified in order to obtain a reliable clamping device and special forming tools as principal precondition to perform ISF. Exceeding the loads limit must also be considered when adapting a robot and also the capability of to generate a clear tool-path. Callegari et al. compared the performance of a robot to a

3-axis CNC milling machine and concluded that robots do not fulfill the stiffness requirements of the ISF process, later on, Meier et al. continued this research path with a set-up called roboforming, it consists of one forming robot at one side of the sheet, combined with a second robot that gives support in a mirror way from the other side.

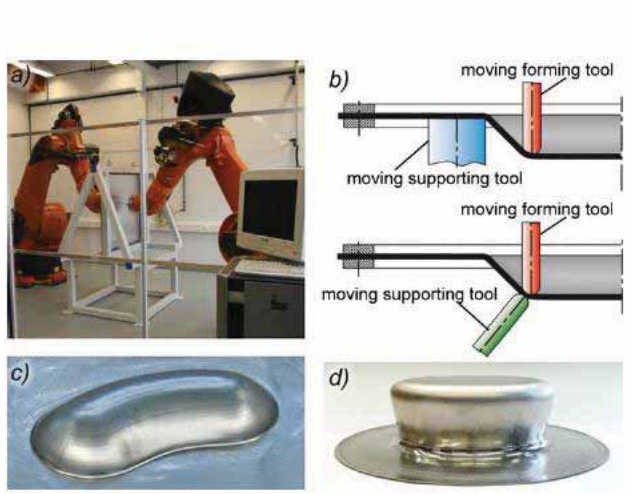


Figure 2. 7 (a) Roboforming set-up, (b) forming strategies,(c) free from surface and (d) undercut, 97° wall cylinder obtained with this technology (Meier et al.,2009).

This is a more complex and expensive process, but it is also available in the industry, as commented previously, our research will be centered in only SPIF with a 3 axis CNC milling machine.

2.3.3 Machines developed for the ISF Process

The TPIF variant was patented by Matsubara in the mid 90´s according to Emmens et al., so based in this concept a Japanese press company, Amino corporation developed what seems to be the only commercial ISF machine.

This machine can work dimensions ranging from 300mm x 300mm, designed especially for research to perform heavy duties from 2500mm x 2750mm. Almost every need can be covered by this offers, nevertheless, you need an initial investment of 300,000 USD, which may be out of budget for must academic institutes.

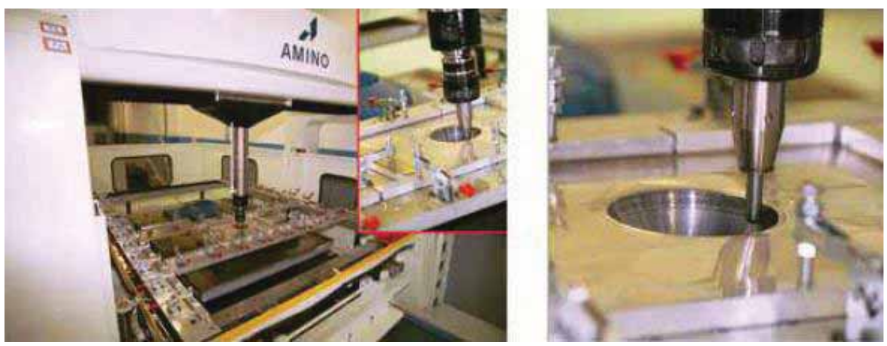


Figure 2. 8 The Japanese Amino Machine (Aserm, 2012)

However, equipment specifically developed for the process has appeared in academic institutes: one of the first ISF machines was designed and manufactured by Allwood et al. in the year 2005 in Cambridge, England.

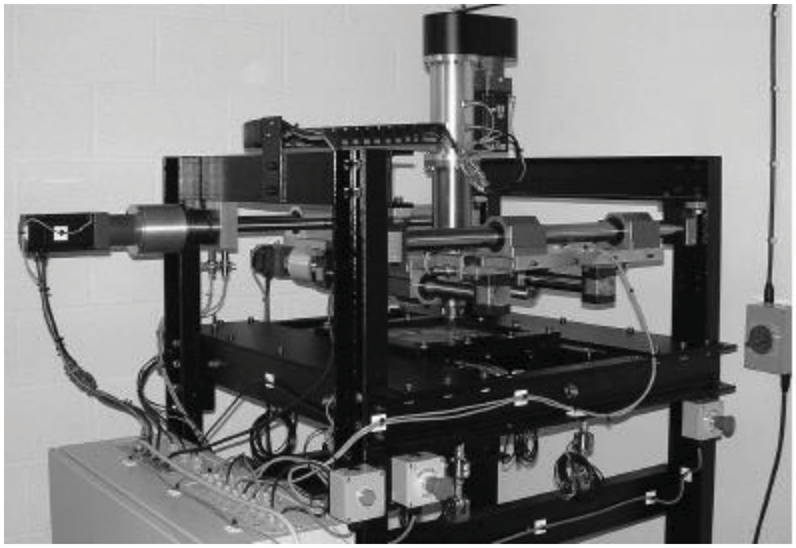


Figure 2. 9 Allwood ISF Machine (2005)

Also Marabuto et al. in the year 2011 designed and built a machine specially for SPIF in the University of Aveiro in Portugal named “SPIF-A”. It uses parallel manipulators in a Stewart platform in order to have more mechanical control of the loop, this also makes the machine gain 2 more degrees of freedom and reduces the moving mass of the system.

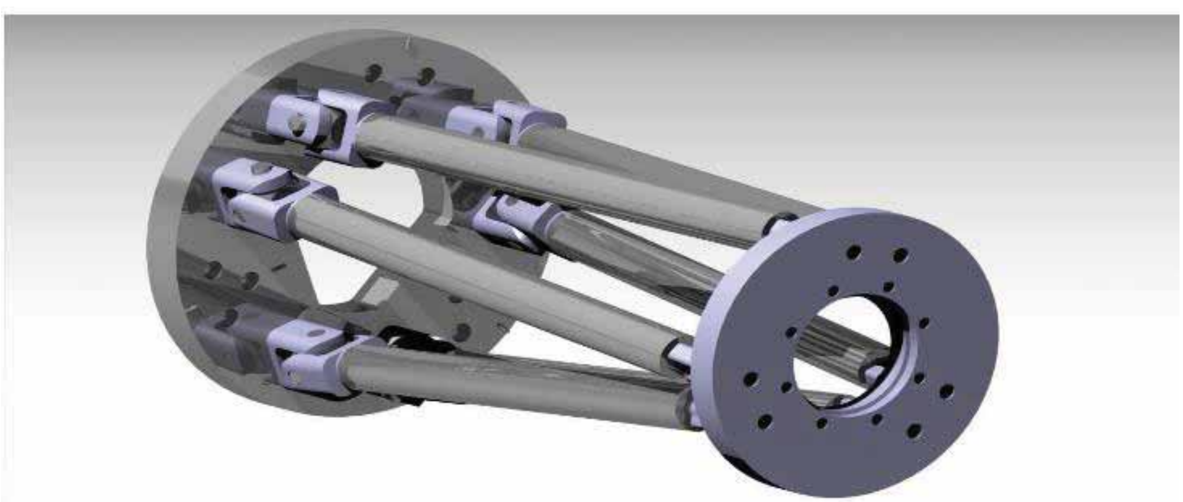


Figure 2. 10 Stewart Platform designed for SPIF-A (Marabuto, 2011)

The machine was built with these specifications

- Parallel kinematics employing a Stewart platform and a 6 by 6 scheme.
- Tool holder, including a passive punch with interaction mechanism
- Vertical stroke of 400 mm;
- Work area of 600x600 mm;
- Maximum axial load of 13KN and bending load of 6,5 KN.

2.4 Conventional Stamping

This process is very common in the industry due to its easy set-up and high production rates. However, according to Hofmann et al., hybrid sheet metal composites steel has to be well-established due to the research that has been made in recent years, he claims there is insufficient knowledge about their forming characteristics in the deep drawing processes. Stiffness increasing composites consists of two metal sheets and viscoelastic damping layer in-between. Due to this, he made an experimental research of the behavior of this type of materials only in deep drawing processes with aluminum alloys, these materials are more commonly used in the automotive industry and his objective was to stablish a methodology to evaluate and assess deep drawing parts of sheet metal composites with a stiffness increasing layer.

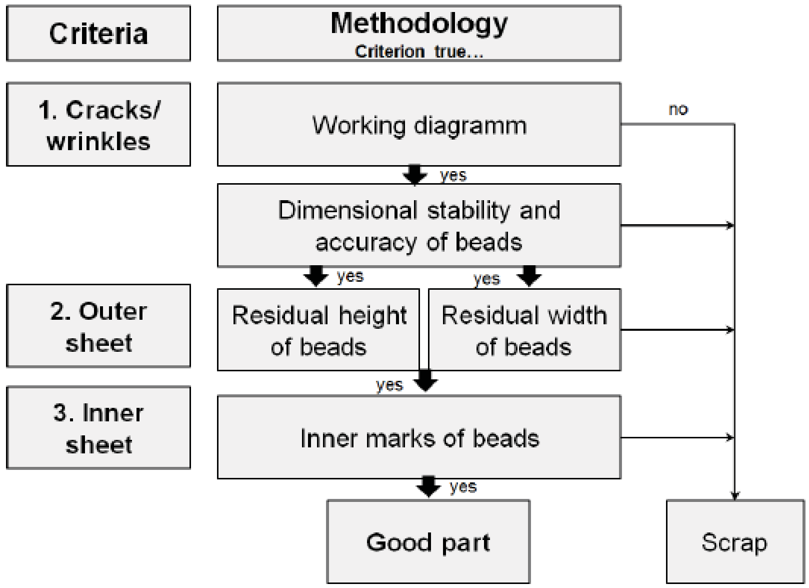


Figure 2. 11 Methodology for evaluating deep drawability of one-sided stiffness increasing sheet metal composites (Hofmann et al.,2016)

Concerning the research made about the comparison in these two processes it has several points to be discussed, for example in the year 2012 Ingarao et al., proposed a work based on the material wasting and energy consumption in incremental forming and stamping processes.

This work has a notable environmental concerning due to the high total-energy released CO_2 emissions which are the 40% of the total global energy released.

Another interesting fact from IEA (International Energy Agency) from the year 2009 is that iron and steel processing is responsible for the 30% of the industrial CO_2 emissions, while the 32% of the total carbon emission arise from production and processing of metallic materials such as iron, steels and aluminum.

The aim of these authors was to develop sustainability guidelines and to promote discussion on limitations, advantages, savings, drawbacks offered by different technologies within sheet metal forming field, in particular the two processes that will be developed as principal in the research of this thesis.

Both processes are analyzed from two points of view: quantification of energy required to develop the deformation and material use in each one.

For this research two aluminum alloys were used; AA-1050 and AA-5754 which are 2 materials commercially used due to its purity of 99% Al. (1050) and 92-97% Al (5754).

For the SPIF process a Mazak vertical machine was properly equipped to carry out the process, also a 45° angle was chosen for all cases, 8 experiments were made.

The energy required can be calculated with the force components along the corresponding tool movement, spire after spire, which moves first along the z-axis, so it can be calculated knowing the force value and the magnitude of the z-direction displacement. For the x component the energy is absorbed while the punch moves along the x-direction, more particular its magnitude can be calculated by the force values in x and y and the x-component, y-component of the displacement.

For the Stamping process a numerical validated simulation was used, the explicit commercial code Dynaform was utilized to reproduce the process from a CAD model.

At the end of the simulation the punch load vs punch stroke curve was determined and the surface underneath the load curve was calculated to obtain the deformation energy.

Figure 2.12 shows a graph proposed by Ingarao et al., comparing the results obtained during their research. They concluded that SPIF releases a considerably higher amount of energy during the process giving conventional stamping a clear path of saving energy

G. Ingarao et al. / Journal of Cleaner Production 29-30 (2012) 255–268

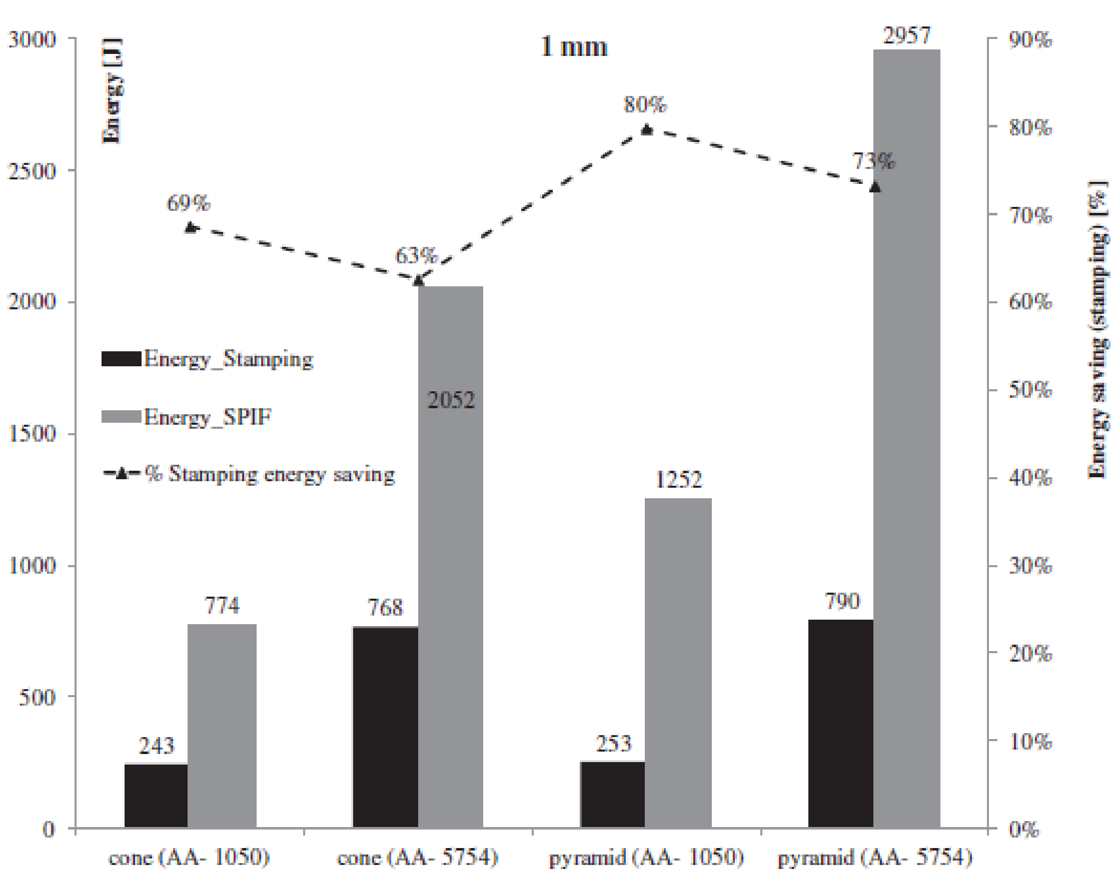


Figure 2. 12 Energy levels and savings for 2 different processes for 1 mm sheet thickness. (Ingarao et al 2012)

In all the cases the energy consumption in SPIF results in a higher value due to the total displacement during each process and thus, contributing to the 2 factors of energy (force and displacement), so it can be said that ecologically speaking, stamping is highly preferable.

It was also found another comparison between these two processes in the year 2016 by Al-Ghamdi et al., in which the formability of roll-bonded steel-Cu was compared in sheet metal incremental forming and stamping.

The results explain that the formability of the composite sheets for both processes increase as the annealing temperature rises. The annealing is more influential on the stamping than in the SPIF.

The SPIF process exhibits higher formability than the stamping in this case, however with increasing annealing temperature and tool diameters the results may differ.

Material	SPIF	Stamping	% Increase
Al-3003 [29]	1.06	0.35	202
Al-2024-T4 [29]	0.81	0.22	268
Steel [29]	1.07	0.33	224
Ti pure [29]	0.99	0.36	175
Brass [29]	1.04	0.37	181
Cu/steel [current] (minimum)	1.33	0.13	923

Table 2. 3 increase in formability SPIF/stamping (Al-Ghamdi 2016)

It is clear that for this material SPIF is a better option speaking in terms of formability and in the Figure 2.15 it can be observed a graphical comparison in formability with the normalized radius in both processes.

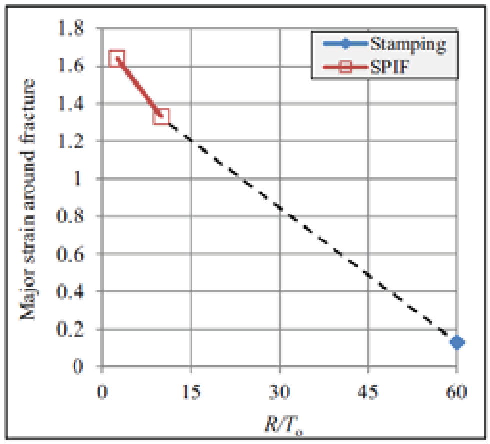


Figure 2. 13 Normalized radius vs formability of Steel-Cu composite sheet metal (Al-Ghamdi 2016

As it was exposed in this chapter, many authors have made experimental research in SPIF regarding parameter modification, heating up of the sheets and closer to our research topic, Al-Ghamdi et al., came very close, in studying a comparison of the formability in sheet metals using SPIF and Stamping.

Also, Ingarao et al., used these two processes to the comparison of energy and material consumption, more specifically to ecological means, stamping process was simulated using a very reliable approach according to the author and the SPIF was performed with a conventional 3 axis milling machine adapted for the process.

This tells us there is a gap in literature in the comparison of two sheet metal forming alternatives which are available in the industry.

For instance, there was no research found in what respects the manufacturing time comparison between these processes, furthermore there are many other parameters which can be compared between these processes like repeatability, precision and resistance by which it is a justifiable fact to proceed in this research project to clarify and expose this experimental comparison.

All the manufacturing processes were conducted in the university facilities and

for the next chapters the methodology and conclusions of these points will be explained.

CHAPTER III – Methodology and Costs

3.1 Introduction

As explained in chapter 2, several comparisons between these two processes have been made regarding energy requirements and formability but none evaluated manufacturing, cost, time, deformation resistance and precision. Based on the available facilities at the Universidad de las Americas Puebla, the CNC milling machine and the Universal Testing Machine (UTM) were adapted for the SPIF and the Stamping process respectively. The equipment, along with the whole testing procedure will be described in the next sections, followed by the cost estimation and data post-processing.

3.2 Experimental Set-up

3.2.1 *Forming Equipment*

For the SPIF process, the experimental work was carried out on the CNC EMCO Mill Concept 55 shown in Figure 3.1, which has a maximum motor force in the Z axis of 1KN.

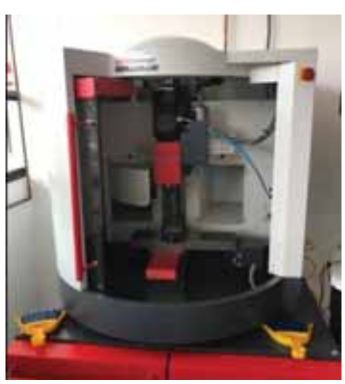


Figure 3. 1 CNC Milling machine Emco concept MILL 55

Work Area	
Travel in X/Y/Z	190/140/260 mm
Distance spindle nose	77-337 mm
Number of axes	3rd (4th optionally)
Rapid motion	2m/min
Work feed X/Y/Z	0-2 m/min
Feed force in X/Y/Z	800/800/1000 N
Clamping area	420x125 mm
Max.table load	10 kg
Milling spindle	
Tool holder	EMCO similar SK30
Number of tools	8
Max. speed	3500 rpm
Max drive power	.75 KW
Max. torque	3.7 Nm

Table 3. 1 Main specs of Emco Concept Mill 55

For the Stamping process the Universal testing machine was adapted for the procedure as shown in Figure 3.2

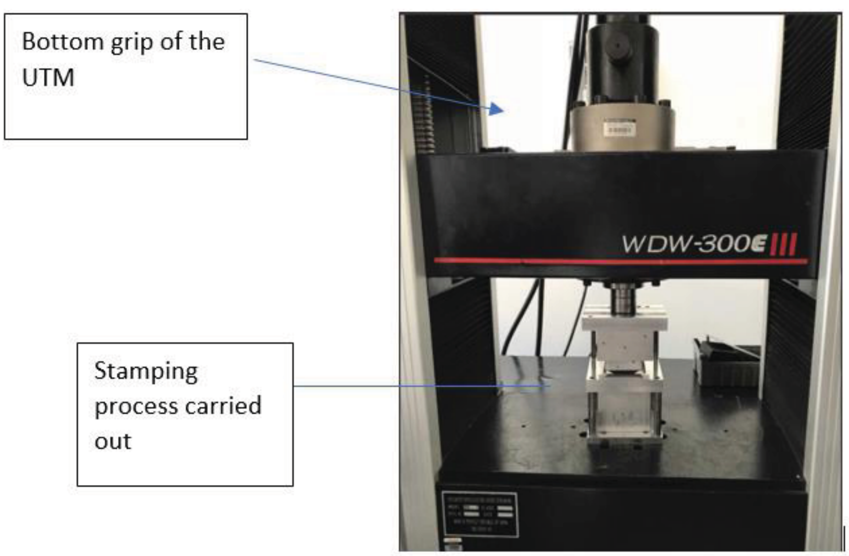


Figure 3. 2 Universal testing machine (UTM) Stamping process

The main specifications of the machine are listed below, for further information the specification sheet of the machine is included in appendix A.

Main Parameters	
Max load capacity	300 KN
Accuracy of the load	+-.5%
Measuring range of test load	.4% - 100%
Resolution of load	.001% FN
Deformation measuring range	.2% -100%
Deformation measuring accuracy	+- .5%
Resolution displacement	.001 mm
Measuring accuracy of displacement	+- .5%
Speed range	.005 mm/min – 500 mm/min
Accuracy of speed	+- .5%
Max tensile travel	600 mm
Max compression travel	600 mm
Width for testing space	760 mm
Overall dimension	1870x770x2558 mm
Power supply	7.5 KW AC 380V
Weight	1660 Kg

Table 3. 2 Main parameters of the universal testing machine

The next figure shows the main components of the UTM and the place were stamping takes place.

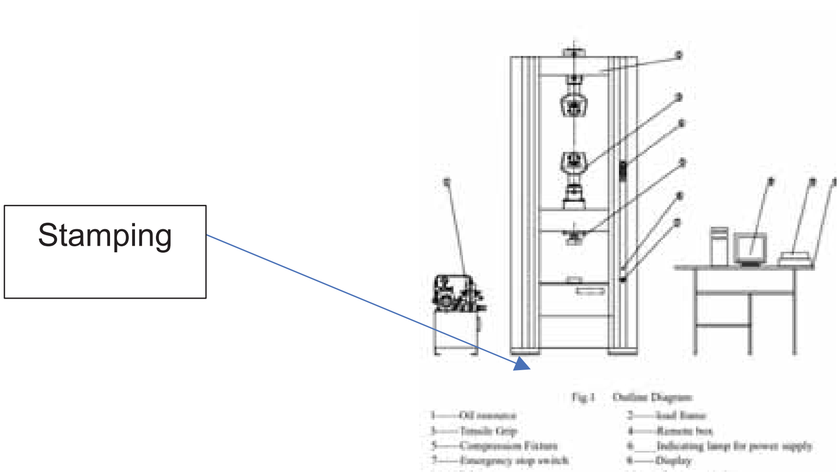


Figure 3. 3 Main components of the Universal testing machine

3.2.2 Other pressing machinery available for this process

As it will be shown, a machine with a compression force of 30 KN or more is needed to perform this process. Instead of the UTM, many hydraulic presses are available in the market the only specification needed is to have 30 KN and a Stroke of 500 mm.

Figure 3. 4 Mikel´s Hydraulic press 30KN

Figure 3.4 shows an example of such machine, this press is one of the basic options available in the market, the prices round the $10,000 pesos, the only difference is that the load vs stroke measurement cannot be recorded as with the universal testing machine.

3.2.3 Sheet Clamping Fixture for SPIF and dies for Stamping

A fixture system composed of a bottom plate, four supports, a clamping plate and a top plate was designed, in collaboration with other members of the honors program, and fabricated for this project (Figure 3.5). the design was based on similar concepts proposed in the literature and customized for the available CNC milling machine.

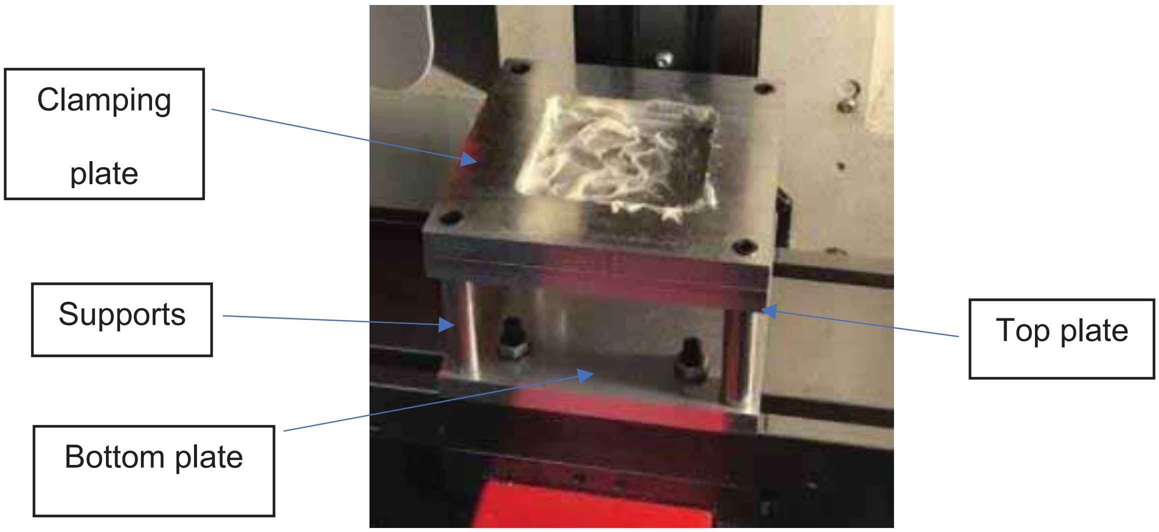


Figure 3. 5 Clamping device set-up for ISF

The blank size is 100mm x 100mm for obtaining parts in the size of those parts, the available literature and paired with the dies manufactured for the stamping process in order to make the corresponding comparisons between them. The working surface measured 75 x 75 mm, the 3 plates are made of Aluminum 6061 and the supports are made of stainless steel AISI-304.(drawings included in Drawings section).

For the Stamping processes both dies were fabricated from an aluminum block stock. Using the available software and CNC machine the dies were manufactured in the lab using the CAM manufacturing option as it can be seen in Figure 3.6 .

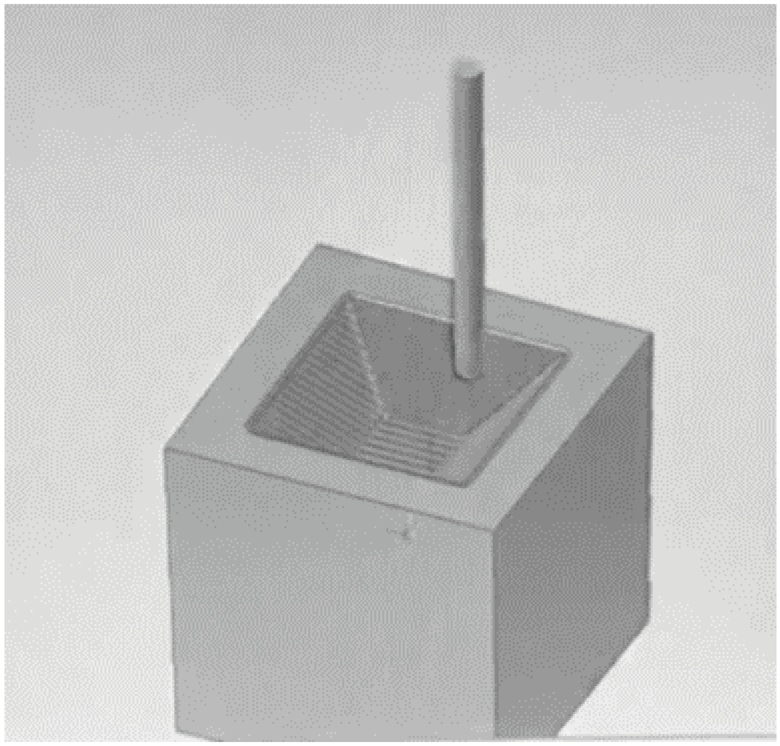


Figure 3. 6 CAM simulation of the bottom die

The complete assembly was finished and then exported to the CAM program.

The complete drawings, assembly and list of parts can be found in the Drawings section. the idea is to deep draw the same part that will be manufactured in the SPIF process to compare both manufacturing processes and the final product quality.

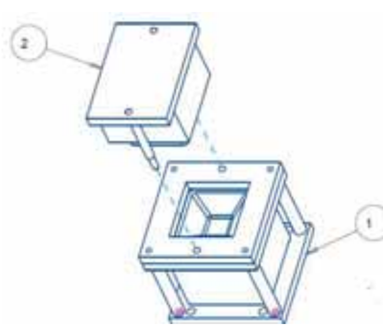


Figure 3. 7 Assembly of upper and lower dies

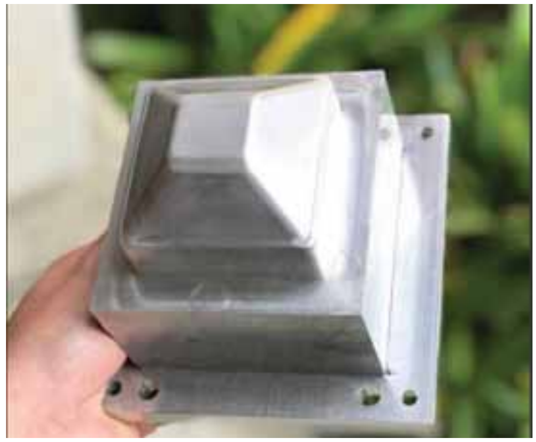


Figure 3. 8 Punch (upper die)

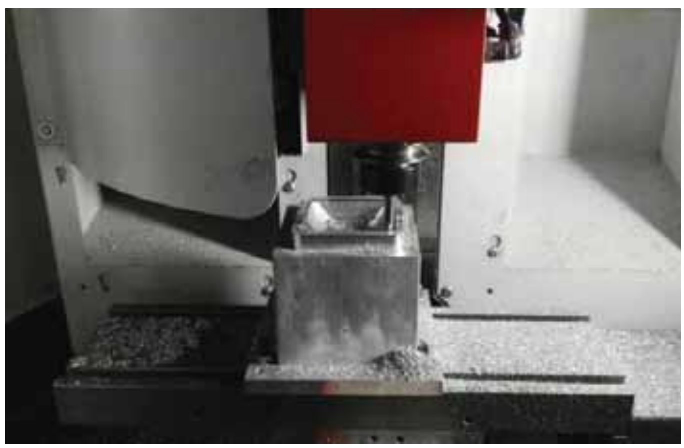


Figure 3. 9 lower die manufactured in the CNC milling machine

As explained previously, the die set was produced in the CNC milling machine, the processing time was of approximately of 16 hours.

3.3 Forming Tools for SPIF

Hemi-spherical forming tools were bought in several end diameters of low carbon steel .From the purchased tool set, three tools were selected in the diameters listed below for thermo-chemical treatment.

Tool	Diameter
1	4.29 mm
2	6.34 mm
3	7.92 mm

Table 3. 3 Forming tools diameter

A thermo-chemical treatment was applied to the tools, because during the SPIF process elevated temperature and friction is present, so a tool with an enhanced hardness and wear resistance in all its surface is needed.

In collaboration with Dr. Rafael Carrera, a nitriding process was held following the next procedure; the tools were exposed in a container with a nitriding atmosphere at 600°C during 22 hours to absorb the nitrogen and create a case- hardened surface to decrease friction and enhance the surface roughness of SPIF process.

Figure 3. 10 Untreated (A) and Treated tools (B)

Treated tool of 6.34 mm diameter was used during the whole experimentation and procedure of the present work, also the lubrication during the process is a very important parameter in order to reach a high-quality surface roughness; for the present work lard was used.

3.4 Blank materials

For both processes, the blanks were stainless steel AISI 304 (0.5 mm thick) with an elevated concentration of chrome and nickel. This only material was selected for the sake of results generality.

Grade		C	Mn	Si	P	S	Cr	Mo	Ni	N
304	min.	-	-	-	-	-	17.5	-	8.0	-
	max.	0.07	2.0	0.75	0.045	0.030	19.5		10.5	0.10

Table 3. 4 Composition specification SS-304

Grade	Tensile Strength (MPa) min	Yield Strength 0.2% Proof (MPa) min	Elongation (% in 50mm) min	Hardness	
				Rockwell B (HR B) max	Brinell (HB) max
304	515	205	40	92	201

Table 3. 5 Mechanical properties SS-304

This material is the most versatile and widely used stainless steel, available in the widest range of products, forms and finishes due to the excellent forming and welding characteristics, it also has a great corrosion and heat resistance. Some of the most common applications are sinks, troughs and storage equipment particularly in the beer brewing, milk processing and wine making industries.

3.5 Tool path generation

Having CNC equipment, clamping devices and forming tools, the only missing part of the basic SPIF system was the tool-path. While arbitrary parts require the commonly used CAM/CAD procedure, the basic SPIF part formed in this investigation made suitable a program that abridged the process. This task was achieved with a routine programmed in Python language, capable of automatically generate the tool-path for pyramidal frusta with straight walls. Another feature included in the piece of software was the possibility to generate unidirectional and bidirectional contouring trajectories. Figure 3.10 depicts the trajectory generated by the automatic tool-path generator.

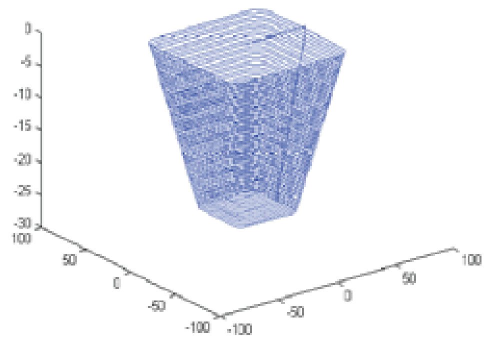


Figure 3. 11 Pyramid path generation

3.6 Costs and time Analysis

For the present work, all the materials were bought in the same materials supplier "Grupo Metalero de Puebla ", so costs may vary depending on the location.

Another fact to take in consideration is the manufacturing time of the soft dies, which as explained in the beginning of the chapter, includes a long designing process and generation of the tool trajectory.

Basically, regarding hardware, the only differences between both technologies are the soft dies and the stamping guides.

The list below shows the list of materials needed to manufacture each component for each process and the price retrieved from the supplier in Puebla.

Raw material STAMPING	material	quantity	cost MXN	
columns	AISI 1045	.5 meter of D= 5/8	$	65.00
bottom plate	AL 6061	6x6 x 1/2" in	$	80.00
upper plate	AL 6061	6x6 x 1/2" in	$	80.00
clamping plate	AL 6061	6x6 x 1/2" in	$	80.00
upper die	AL 6061	100x100x100 mm	$	385.00
lowe die	AL 6061	100x100x100 mm	$	385.00
stamping guides	AISI 1045	.5 meter of D=1/2	$	95.00
die support base	AL 6061	6x8x 1/2" in	$	100.00
		TOTAL	$	1,270.00

Table 3. 6 Material costs for Stamping process

Raw material SPIF	material	quantity	cost MXN	
columns	AISI 1045	.5 meter of D= 5/8	$	65.00
bottom plate	AL 6061	6x6 x 1/2" in	$	80.00
upper plate	AL 6061	6x6 x 1/2" in	$	80.00
clamping plate	AL 6061	6x6 x 1/2" in	$	80.00
SPIF TOOLS	A2-Tool grade Steel		$	900.00
		TOTAL	$	1,205.00

Table 3. 7 Material Costs for SPIF

It can be concluded that the raw material for both processes has the same price. Afterwards, a design process should be conducted in order to finish the prototype and start the manufacturing.

A design process cost was calculated taking into consideration a starting price of $20 USD which approximately rounds the $400 mexican pesos per design hour.

Design Stamping	design hours	cost per hour MXN	total cost MXN
clamping device	24	$ 400.00	$ 9,600.00
stamping dies	40	$ 400.00	$ 16,000.00
die support base	1	$ 400.00	$ 400.00
stamping guides	4	$ 400.00	$ 1,600.00
total	69	total	$ 27,600.00

Table 3. 8 Design costs for Stamping

Design SPIF	design hours	cost per hour MXN	total cost MXN
clamping device	12	$ 400.00	$ 4,800.00
path program	4	$ 400.00	$ 1,600.00
total	16		$ 6,400.00

Table 3. 9 Design costs for SPIF

The design costs of stamping are considerably higher due to the complexity of designing the dies in order to fit the requirements.

For the manufacturing process, many specifications must be made in order to get an accurate estimation of the final product.

In first place a material should be selected, since the soft dies are made of aluminum, a very ductile and easy machinable metal, the costs are more affordable as if compared with steel.

It is important to tell that the main of objective of this process is not mass production, but it is aimed to prototype a small batch of parts with the soft dies, otherwise, steel should be used with a special surface coating in order to increase the wear and corrosion resistance of the material.

The tolerances and surface roughness of the dies are a very important variable in the manufacturing cost of this part, the costs have an exponential increase due to the time needed to achieve these specifications.

Since the tolerance and the surface roughness of the soft dies are not as important as in the massive production case, a standard measure can be used, nevertheless, these specifications should be included when manufacturing these parts.

Some typical values of surface roughness and tolerances were retrieved and are presented in the next table according to the machining operation.

	Tolerance Capability —Typical		Surface Roughness AA—Typical			Tolerance Capability —Typical		Surface Roughness AA—Typical	
Machining Operation	**mm**	**in**	**μm**	**μ-in**	**Machining Operation**	**mm**	**in**	**μm**	**μ-in**
Turning, boring			0.8	32	Reaming			0.4	16
Diameter $D < 25$ mm	±0.025	±0.001			Diameter $D < 12$ mm	±0.025	±0.001		
25 mm $< D <$ 50 mm	±0.05	±0.002			12 mm $< D <$ 25 mm	±0.05	±0.002		
Diameter $D > 50$ mm	±0.075	±0.003			Diameter $D > 25$ mm	±0.075	±0.003		
Drilling*			0.8	32	Milling			0.4	16
Diameter $D < 2.5$ mm	±0.05	±0.002			Peripheral	±0.025	±0.001		
2.5 mm $< D <$ 6 mm	±0.075	±0.003			Face	±0.025	±0.001		
6 mm $< D <$ 12 mm	±0.10	±0.004			End	±0.05	±0.002		
12 mm $< D <$ 25 mm	±0.125	±0.005			Shaping, slotting	±0.025	±0.001	1.6	63
Diameter $D > 25$ mm	±0.20	±0.008			Planing	±0.075	±0.003	1.6	63
Broaching	±0.025	±0.001	0.2	8	Sawing	±0.50	±0.02	6.0	250

Table 3. 10 typical Surface roughness for machining operations (Groover)

In the drawings given to the manufacturer, it should be indicated if a certain tolerance and roughness is needed, otherwise, a standard value will be taken.

The manufacturer will make a quote depending on the complexity of the part, a standard price will be given in terms of cost per hour if the part has a common geometry, otherwise it will be considered in cost per part.

Using the algorithm developed by Ullman to estimate manufacturing costs of mill and lathe, with an exchange rate of $19.00 mexican pesos (MXN) per $1 American dollar (USD) the next analysis will be divided first in SPIF manufacturing costs as separated components, and then, for stamping respectively.

manufacturing SPIF	hour rated USD	time required hr	cost USD	cost MXN
columns	$ 35.00	0.94	$ 32.90	$ 625.10
clamping plates	$ 35.00	1.80	$ 63.00	$ 1,197.00
base	$ 35.00	0.90	$ 31.50	$ 598.50
			total	$ 2,420.60

Table 3. 11 Manufacturing Costs SPIF

manufacturing Stamping	hour rated USD	time required hr	cost USD	cost MXN
columns	$ 35.00	0.94	$ 32.90	$ 625.10
clamping plates	$ 50.00	8.00	$ 400.00	$ 7,600.00
base	$ 35.00	0.90	$ 31.50	$ 598.50
upper base	$ 35.00	0.90	$ 31.50	$ 598.50
upper die	$ 50.00	8.00	$ 400.00	$ 7,600.00
lower die	$ 50.00	8.00	$ 400.00	$ 7,600.00
stamping guides	$ 35.00	2.00	$ 70.00	$ 1,330.00
		28.74	total	$ 25,952.10

Table 3. 12 Manufacturing Costs Stamping

For the manufacturing process, stamping has also a higher cost, due to the stamping dies which need to be manufactured using a CNC milling machine and several tools due to the rounds needed and the roughing of both parts.

CHAPTER IV – Experimental results

4.1 Introduction

This chapter is focused on the evaluation of the experimental results obtained during the processes explained earlier. These results were obtained with the equipment available in the manufacturing laboratories of the university. For both processes 3 pyramids were fabricated with same 45° wall angle to study the performance of each process.

4.2 Conventional Stamping

After testing the stamping dies, good results were obtained from the process, below the 3 experiments are reported with a top and bottom view of the stamped pyramid. In the bottom view a printed pattern can be observed, this will help to measure the material deformation and isotropy in the areas were the material flows to acquire the desired form.

Figure 4. 1 Top view of the 3 stamped pyramids procedure

Figure 4. 2 Stamped pyramid with lard used as lubricant in both sides

Figure 4. 3 Stamped pyramid with lard used as lubricant in the upper side

First the graphs load vs stroke will be presented in each of the 3 cases in order to stablish a relation between these two parameters.

A repeatability pattern can be observed in the graph due to the material normal behavior and the constant stroke and load applied to deform the pyramids.

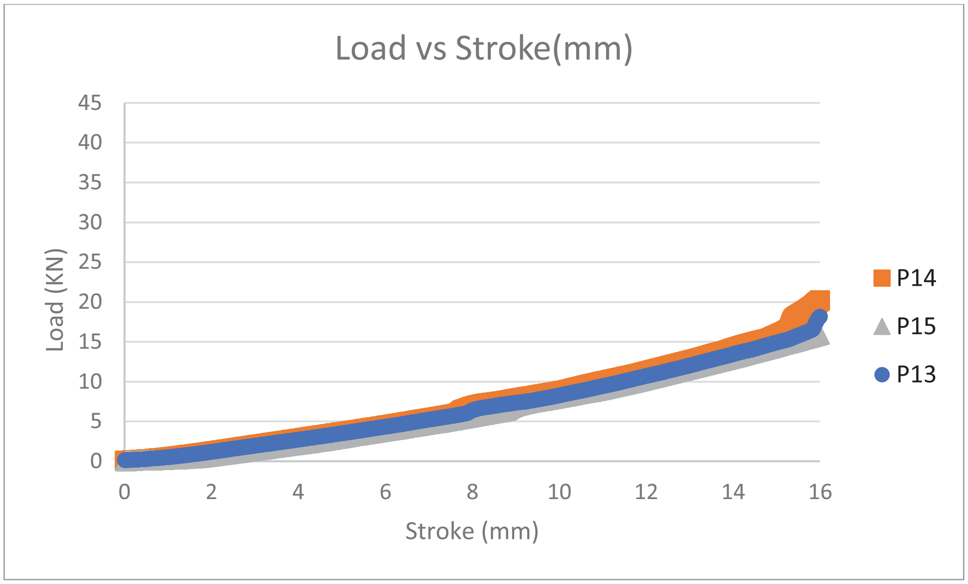


Figure 4. 4 Load vs Stroke Graph Stamping procedures

Then a deformation study was carried out by measuring the deformation in each pyramid wall utilizing a digital calibrator for the measurements as show in Figure 4.5.

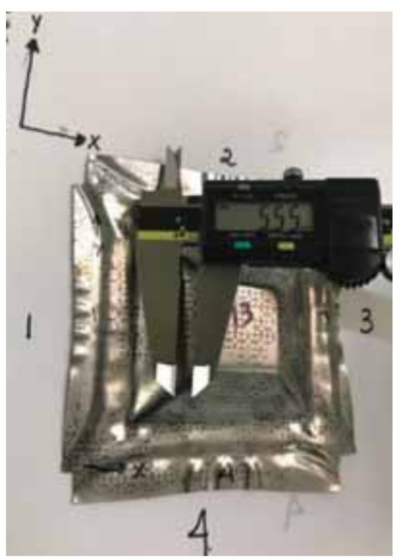


Figure 4. 5 Deformation measuring

Each pyramid wall was labeled, also X and Y axis were stablished in all 3 pyramids in order to have more accurate measuring results.

The data was processed and δM was calculated by using the biggest elongation of the ellipse formed divided by the original diameter of the circles printed in the blank.

$$\delta\mathrm{M} = \frac{D_{ellipse} - D_{circle}}{D_{circle}}$$

After computing all data, the next graph was obtained in Figure 4.6.

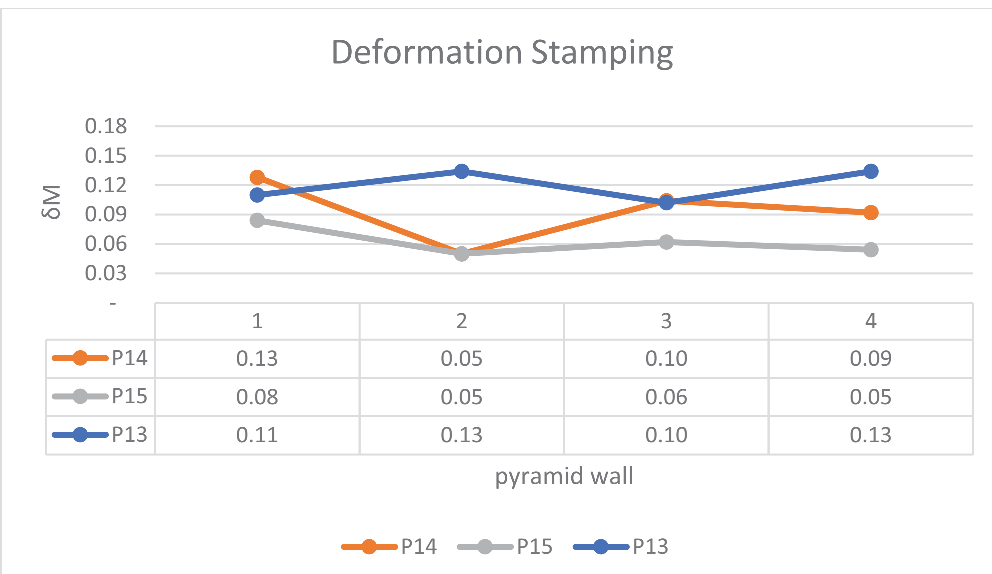


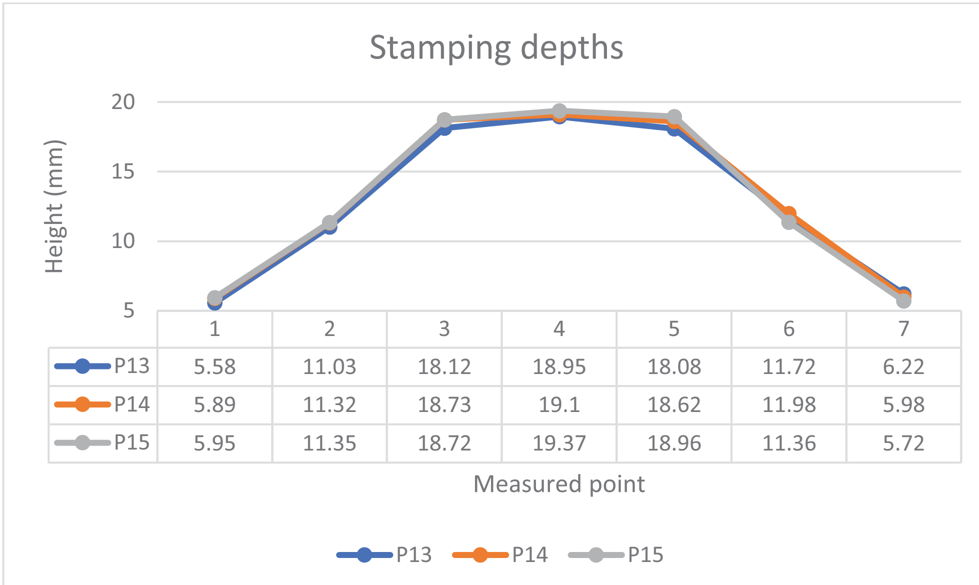
Figure 4. 6 Deformation in stamped pyramids

As it can be observed the deformation that occurred in this process is very small, also good isotropy of the material can be deduced due to the constant deformation retrieved from each wall of the pyramid. Taking into consideration this study, it can be inferred that the blank thickness variation was small, around .05mm.

Then a depth study was conducted in order to see the precision of the process, using a height caliper and the same pattern used for deformation, X and Y axis were labeled, and 7 dots were marked along the X axis of the pyramid at the same points.

Figure 4. 7 Depth measurement using the height caliper.

In Figure 4.8 the computed data may be observed in each of the 3 stamped pyramids.



	1	2	3	4	5	6	7
P13	5.58	11.03	18.12	18.95	18.08	11.72	6.22
P14	5.89	11.32	18.73	19.1	18.62	11.98	5.98
P15	5.95	11.35	18.72	19.37	18.96	11.36	5.72

Figure 4. 8 Stamped pyramid depths results

The repeatability of this process is high due to the die guides and the stamping procedure, the material flows through the punch with good uniformity in the 4 walls. Also, the heights remained at an almost constant value of 19mm.

Our last test will be the resistance of the pyramids, they will be compressed in the Universal testing machine with a deformation velocity of 5mm/min

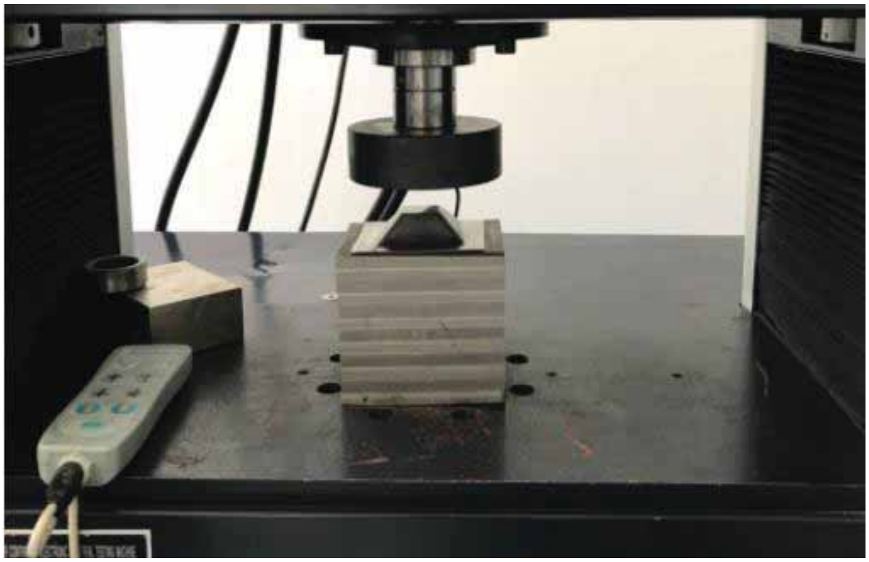


Figure 4. 9 Compression of Stamped pyramids

The computed results are graphed below in Figure 4.10

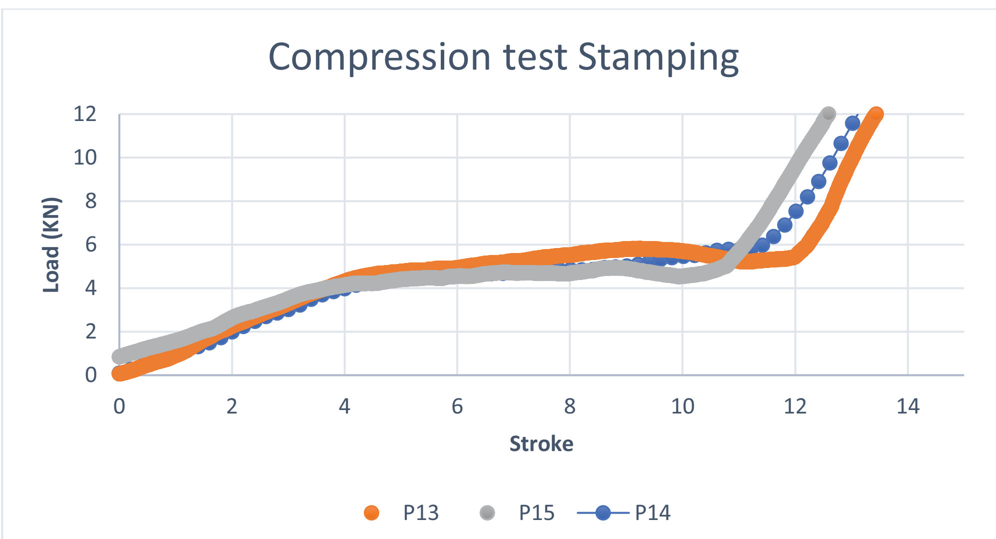


Figure 4. 10 Compression test Stamping results

It can be observed how the material behaves with some linearity up to around 12 KN where the pyramid is already formed and coining increases the force suddenly.

4.3 Single point incremental sheet forming

After perfecting the G-code for the path generation of the pyramid in the CNC and the correct amount of lubrication needed during the process, 3 good experimental results were manufactured, the 3 pyramids were also printed with the pattern to measure the deformation.

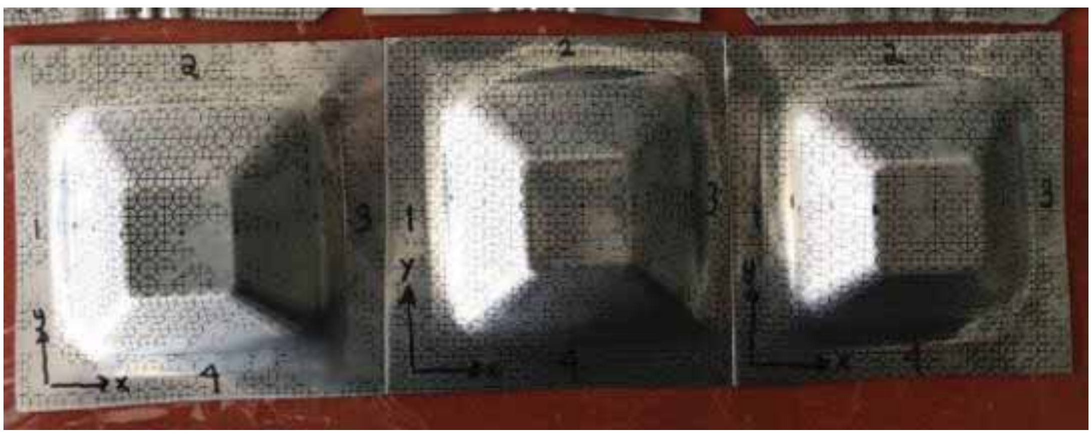


Figure 4. 11 SPIF pyramids.

In order to measure deformation, the same procedure was done (section 4.2), X and Y axis were labeled and 1 measure in each wall of the pyramid was made, the data was processed and δM was calculated by using the biggest elongation of the ellipse formed, divided by the original diameter of the circles printed in the blank.

After computing all data, the next graph was obtained in Figure 4.12.

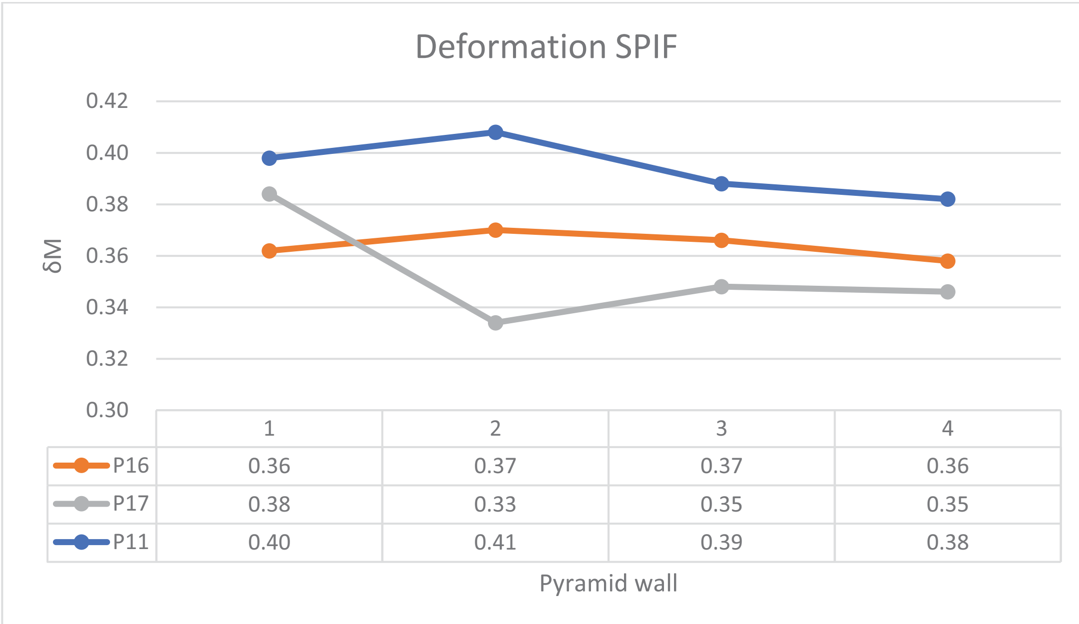
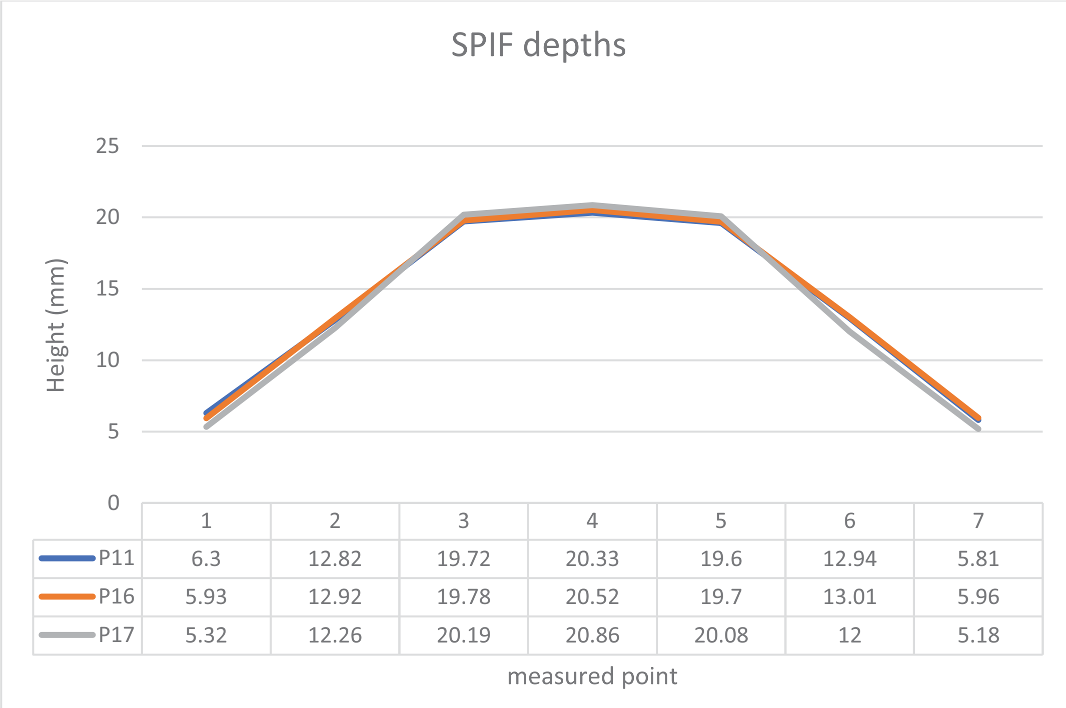


Figure 4. 12 Deformation of SPIF pyramids

The deformation in SPIF pyramids are considerably larger than in the stamped ones, so it can be concluded that the wall thinning in this process is considerably higher, and that the blank thickness is reduced due to the material elongation.

Then, the same heights procedure (section 4.2) was conducted with the SPIF pyramids, using a height caliper.



	1	2	3	4	5	6	7
P11	6.3	12.82	19.72	20.33	19.6	12.94	5.81
P16	5.93	12.92	19.78	20.52	19.7	13.01	5.96
P17	5.32	12.26	20.19	20.86	20.08	12	5.18

Figure 4. 13 Pyramid depths results

As it can be concluded this process attains a higher repeatability even though the blank is subjected to larger deformations, the material flows more uniformly and thus ending in a closer precision height as depicted in the program.

And concluding this chapter, the same resistance test was made, the pyramids were compressed in the Universal testing machine with a Force in the punch of 30KN and a stroke of 5mm.

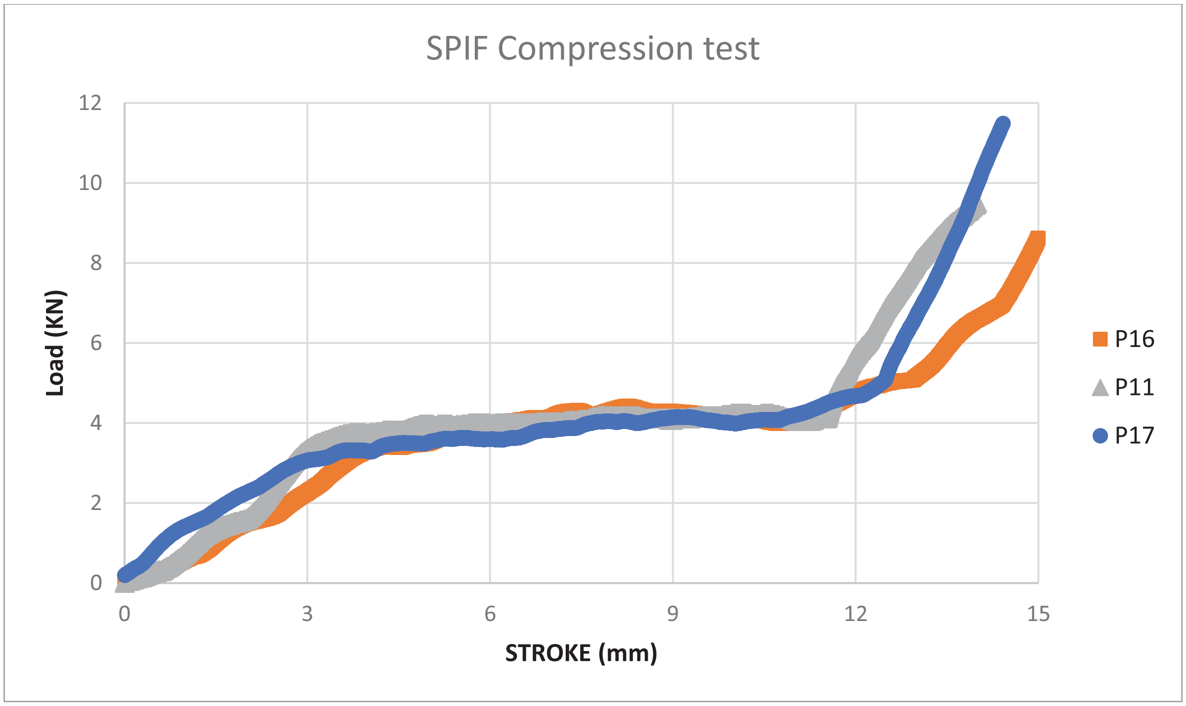


Figure 4. 14 SPIF compression test

It is clear that the SPIF pyramids attain to have a lower resistance due to the wall thinning effect and the large deformation provoked by this manufacturing technique. The pyramid fails at a 4 KN load having a lower value than the stamped pyramids.

CHAPTER V-Conclusions

5.1 Introducción

In this chapter the results previously reported on chapters 3 and 4 will be compared in order to get a final conclusion about which process is better according to these criteria.

It is important to tell that in order to get more accurate statistical data , more samples must be made, nevertheless these results give a clear view of both processes and show a convincing pattern of repeatability among them.

5.2 SPIF and Stamping Comparison

5.2.1 Costs and time analysis

At this point it must be cleared that all cost estimations are not strictly accurate, but taking in consideration the available resources, each process may be a better option.

Speaking in terms of materials both processes requires the same investment, the available machinery must be included, a CNC is extremely necessary when performing each SPIF part, a CNC center costs around $500,000 mexican pesos, and in the other hand, for stamping, an hydraulic press of $10,000 mexican pesos would fit.

The next table shows the comparison between the costs and time analysis made in chapter 3. Note that all these costs are only for preparation of each process and does not include the actual part fabrication.

Phase	time SPIF (hr)	time stamping (hr)	cost SPIF	cost stamping
Raw material	N/A	N/A	$ 1,205.00	$ 1,270.00
Design	12	69	$ 6,400.00	$ 27,600.00
Manufacture	3.64	28.74	$ 2,420.60	$ 25,952.10
Total	15.64	97.74	$ 10,025.60	$ 54,822.10

Table 5. 1 Costs and time comparison

There is a huge difference between the time and costs of these two processes, as it can be seen, the raw materials have approximately the same costs, the engineering hours are required in order to get the final product, this is a combination of knowledge and available machinery, of course if having a CNC milling machine available these costs may apply, in other case a CNC machine rental is rated approximately at $50 american dollars per hour.

It is approximately 5 times more expensive and 7 times longer to prepare for the stamping process, nevertheless, these aren't the only considerations to take into account.

In the next part the experimental results will be tested in order to clarify which process attains a better resistance, precision and deformation.

5.2.2 Experimental comparison

In the last chapter experimental results were exposed for each process, for the deformation comparison, a common scale was used to have an accurate back to back view.

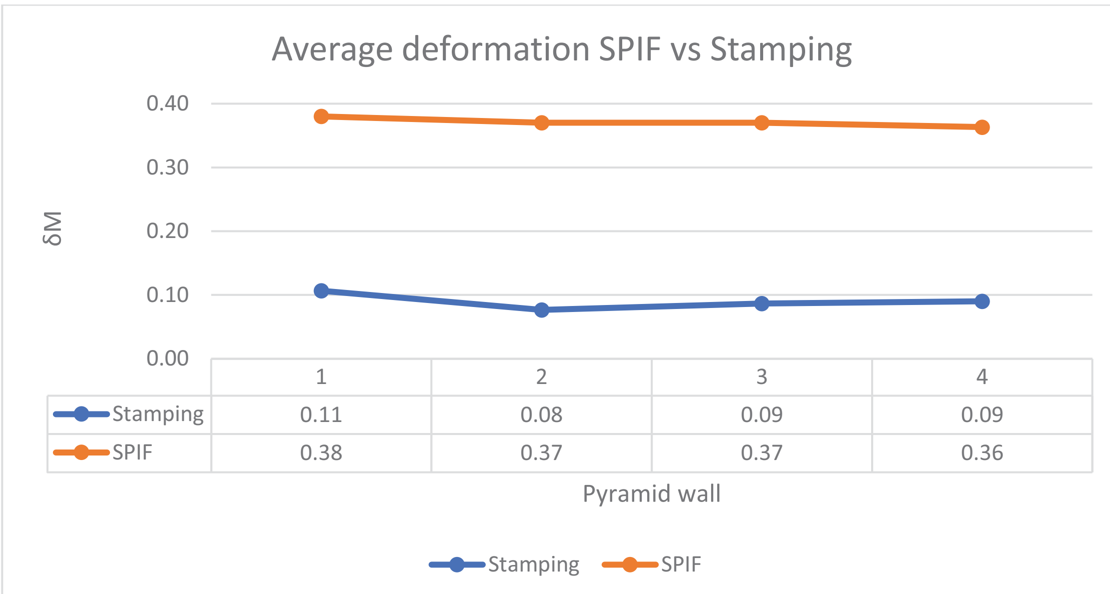
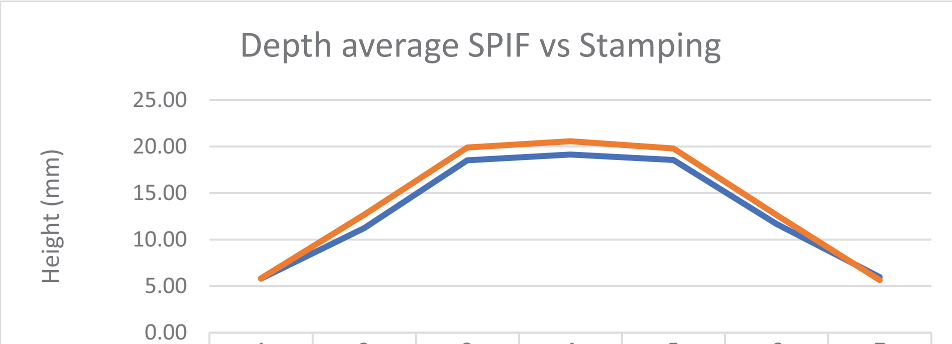


Figure 5. 1 Average deformation SPIF vs Stamping

SPIF pyramids tend to deform 3 to 4 times more in contrast to stamped ones, this tells us that in SPIF, the material is pushed down to the bottom tending to deform much more and thus, causing a wall thinning effect.

For the next comparison the same average scale was made in order to form one SPIF and one Stamped pyramid with the same 7 height points measured.



	1	2	3	4	5	6	7
Stamping	5.81	11.23	18.52	19.14	18.55	11.69	5.97
SPIF	5.85	12.67	19.90	20.57	19.79	12.65	5.65

Figure 5. 2 Depth average SPIF vs Stamping

As it can be deduced from Figure 5.2 the SPIF pyramid reached a higher depth in contrast to the stamped pyramid.

Another hypothesis is that the blank thickness was not considered for the dies, so in each part 0.5 mm are subtracted from the final height, however this could be fixed quickly changing the path program and reducing the height.

And finally, for the resistance comparison, one representative pyramid was taken for each case in order to have a clear tendency of each one.

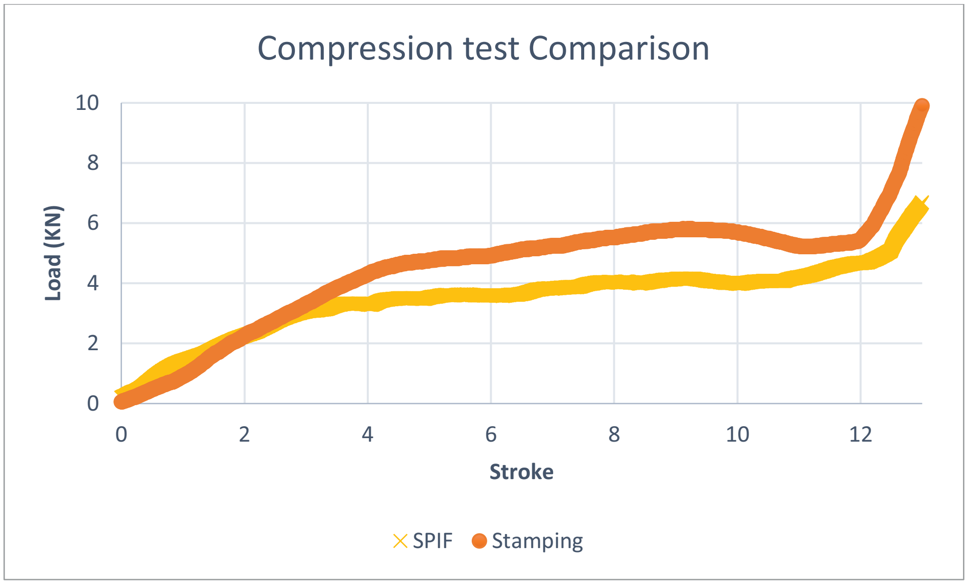


Figure 5. 3 Compression test Comparison

From Figure 5.3 it can be deduced that the stamped pyramid shows a higher resistance, this may be explained from the lower deformation recorded and the lower depth achieved. The wall thinning effect is a determining factor in this test since the SPIF pyramid only needed 4 KN to compress, differently to the 6 KN needed to compress the stamped pyramid.

The main objective of this work is to continue with this investigations in order to apply both processes in a more industrial application, for example in some medical equipment like a prothesis, a car component or some prototype that must be made and taking into consideration the available equipment and knowledge to manufacture the part by the most viable procedure.

5.3 Future Work

For further analysis, scanning the pyramids in order to retrieve real wall thinning measures and a more accurate comparison with the original CAD part should be done.

Also in the simulation field a test of both processes should be done in order to compare the real results to the simulation and depict the differences between both.

APÉNDICES

APÉNDICE A: Specification table of Universal testing Machine

Thank you for selecting our model WDW-300E micro-computer controlled electronic universal testing machine. Prior to use, please carefully read the operation manual. After understanding it fully, you use it. Please take care of it and use it properly so that the machine maintains higher precision and normal running state forever.

1. Application & Scope

It's designed for tension, bend, compression etc, mechanical property test of metal and non-metal. It is suitable for use in science and research institutes, colleges and universities, quality inspection center, and commodity inspection.

2 Main Specification & Parameters

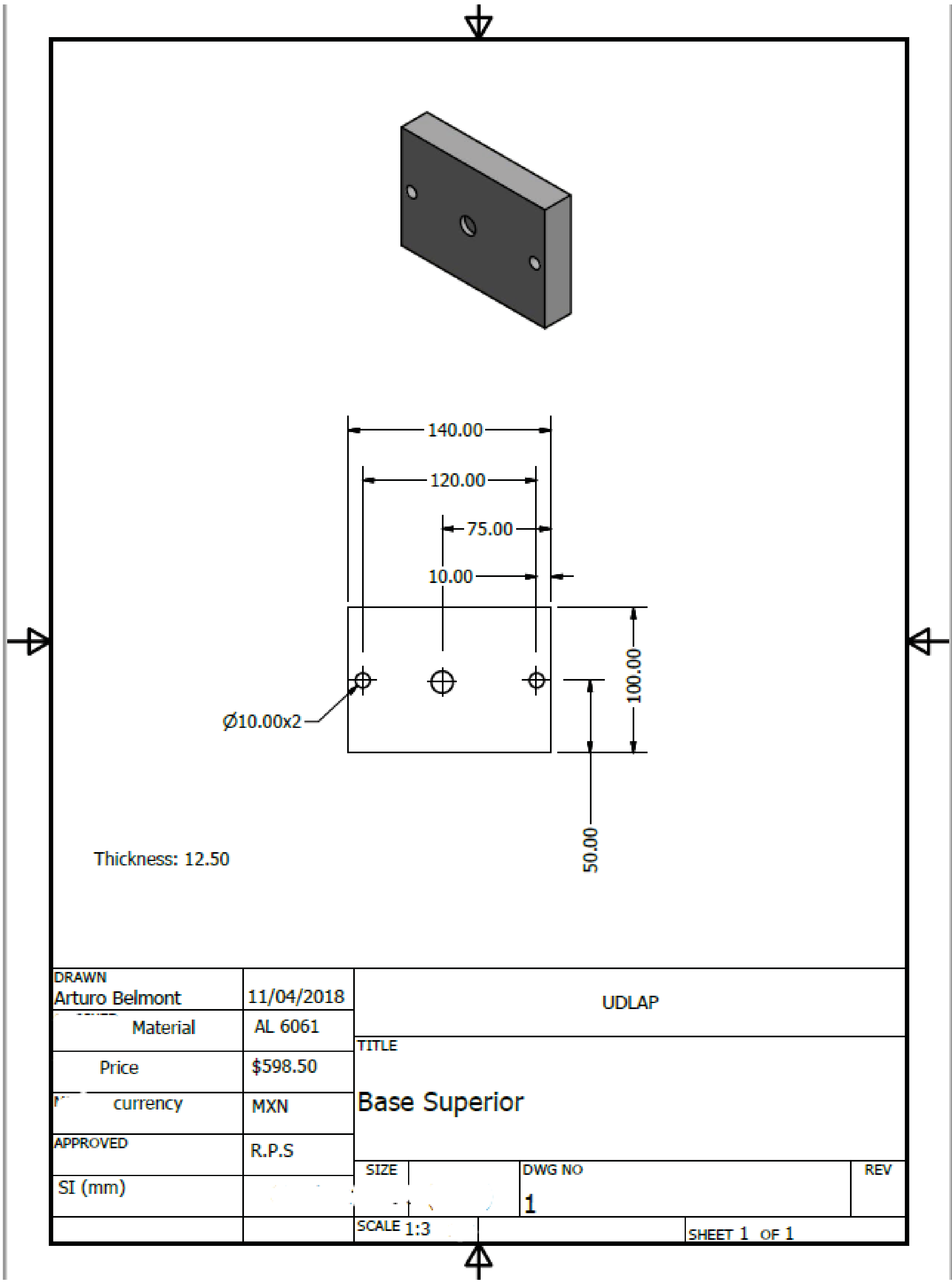
2.1Main Parameters

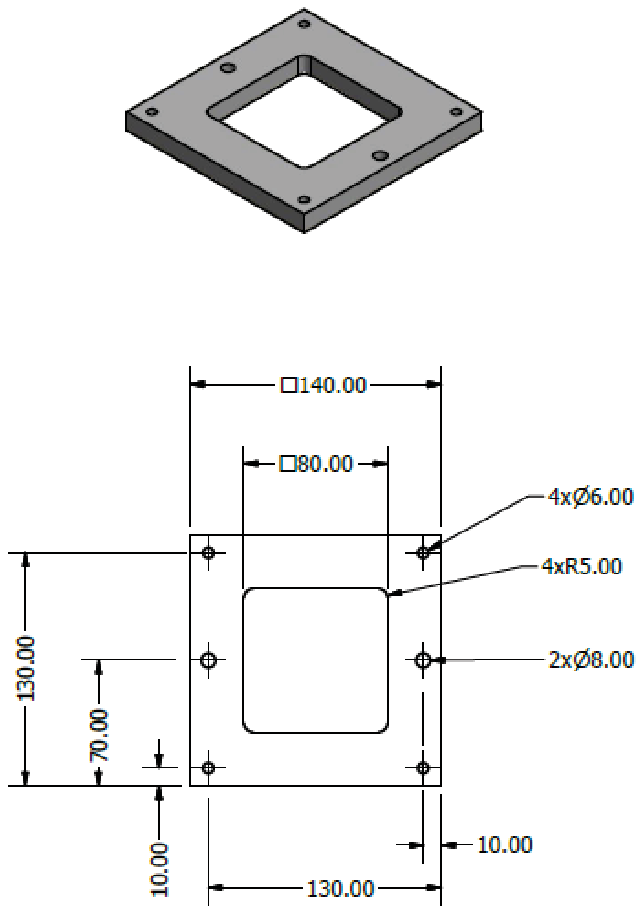
Max. Load Capacity:300kN;
Accuracy of Load: ±0.5%;
Measuring range of test load: 0.4%~100%， auto-shift in full process;
Resolution of Load：0.001%FN.
Deformation measuring range: 0.2%～100%;
Deformation measuring accuracy：within measuring range，relative error of indicating value :±0.5%.
Resolution of Displacement: 0.001mm.
Measuring Accuracy of Displacement：±0.5%。
Speed range：0.005mm/min～500mm/min，stepless;
Accuracy of speed：±0.5%;
Max. Tensile Travel:600mm;
Max. Compression Travel: 600mm;
Width for Test Space:760mm;
Max. travel of crosshead: 1350mm;
Overall Dimension: 1870×770×2558mm;
Power supply: 7.5KW, three-phase AC 380V;
Weight: 1660Kg.

3． Working Condition

3.1 Ambient temperature: 10－35±2℃;
3.2 Relative humidity: ≤80%;
3.3 Around it without vibration, corrosive medium, strong electric-magnetic field interference;
3.4 Fluctuation of power voltage can't be more than ±10% of rated voltage;
3.5 Install it on level solid base, levelness is 0.2/1000;

APÉNDICE B: Drawings





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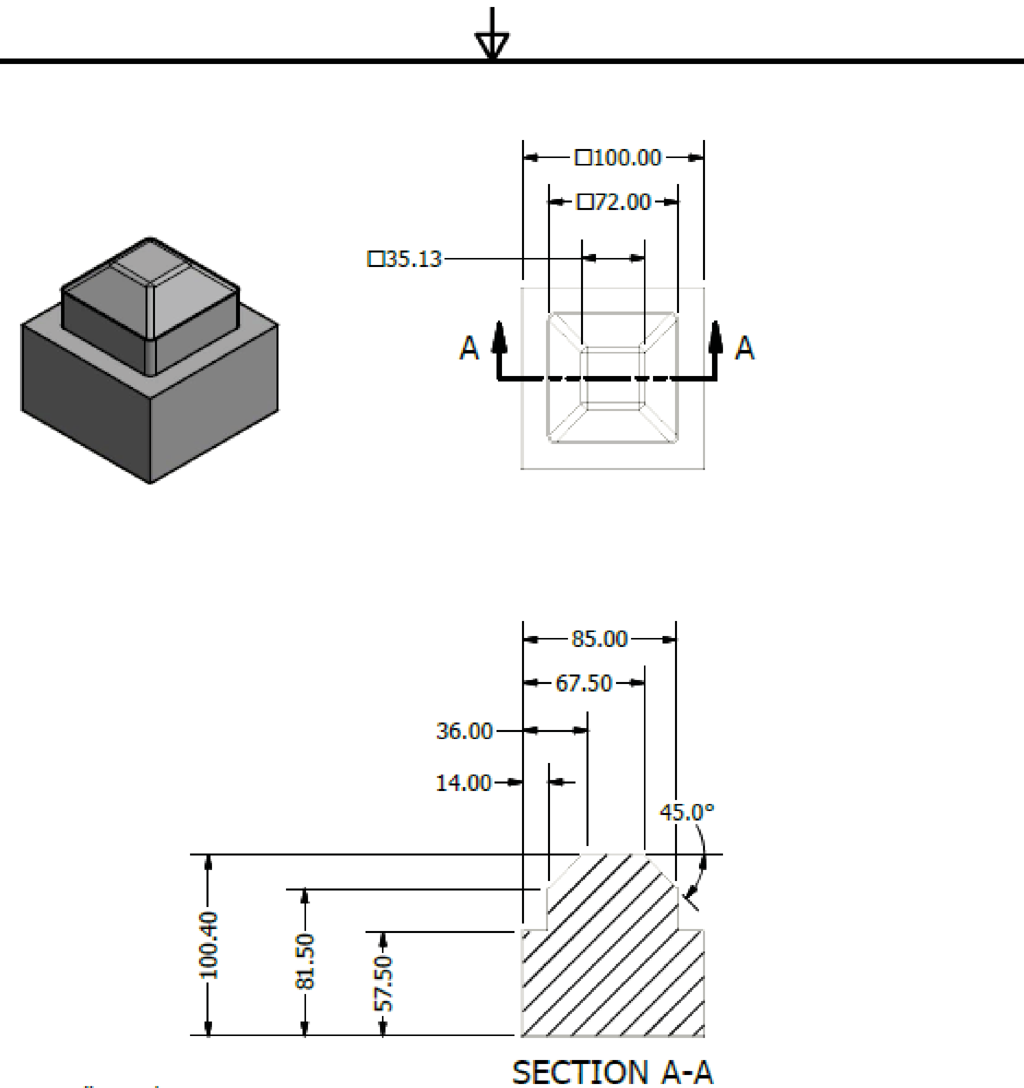

Note: All rounds 5mm

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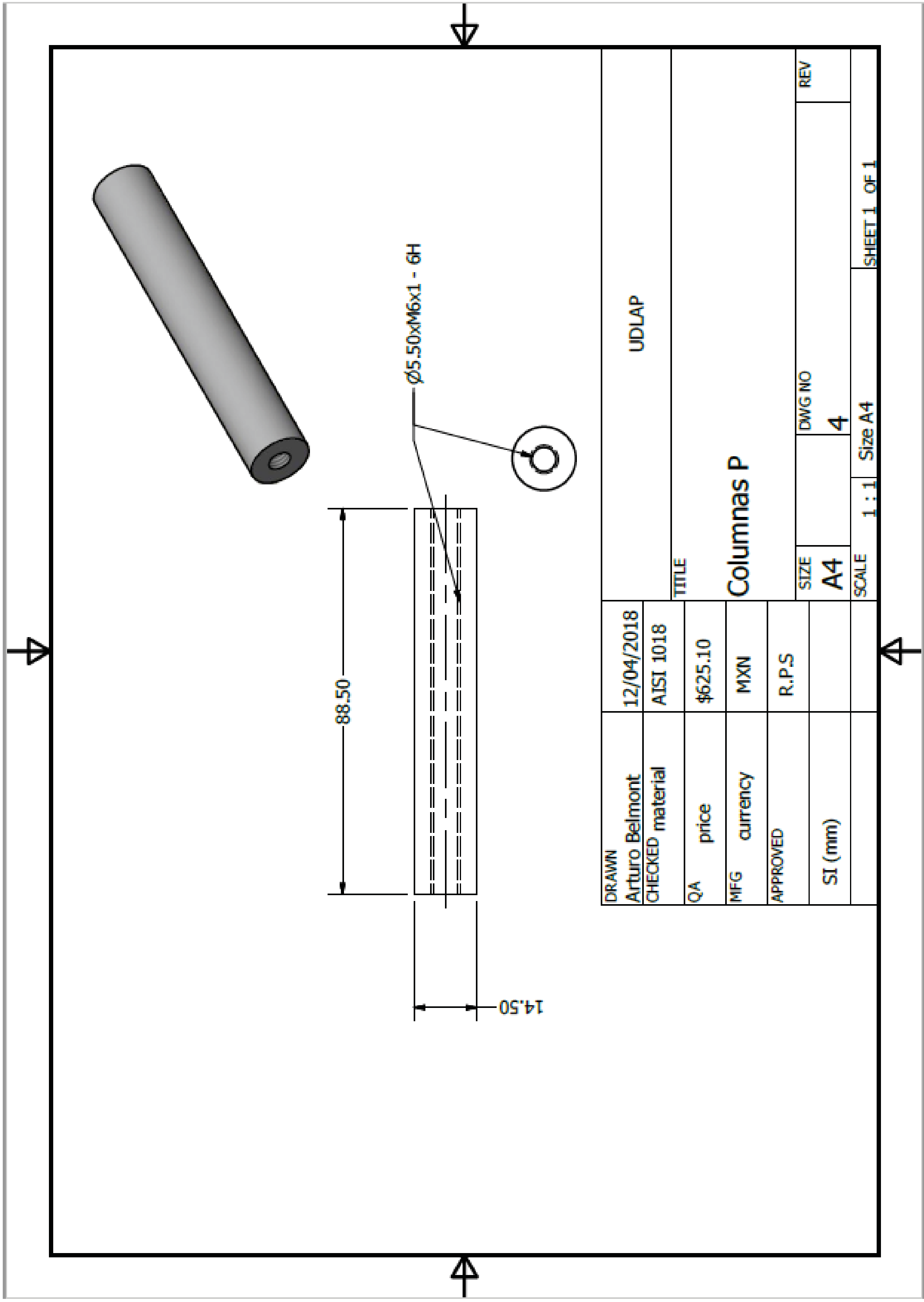
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12/04/2018
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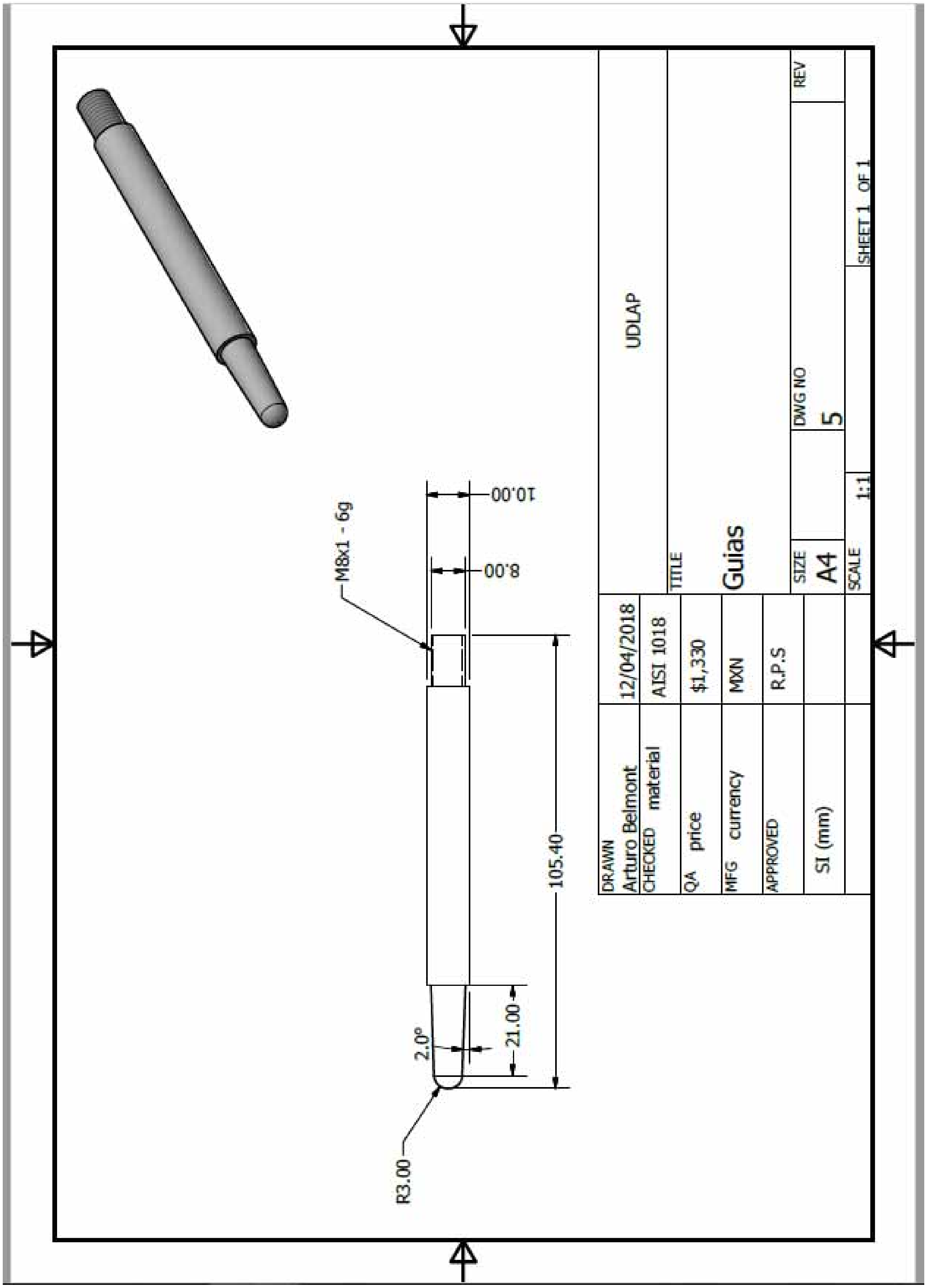
SHEET 1 OF 1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Arturo Belmont
12/04/2018
CHECKED material
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QA price
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DWG NO
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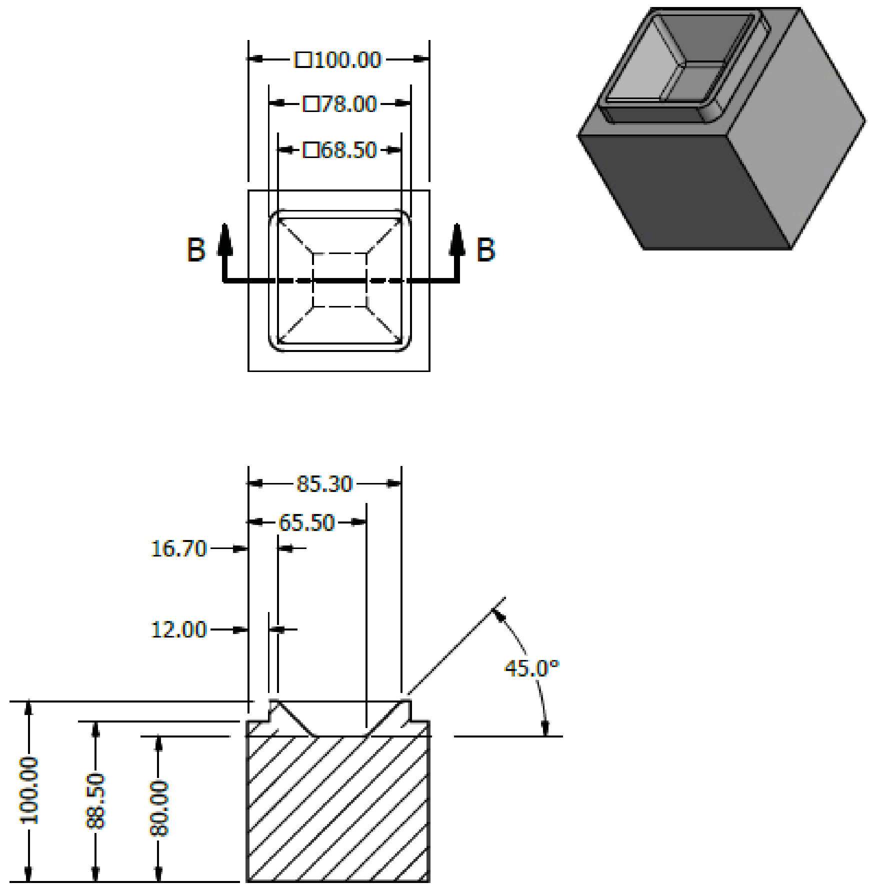
REV
SCALE
1:1
SHEET 1 OF 1



SECTION B-B

Note: All rounds 5mm

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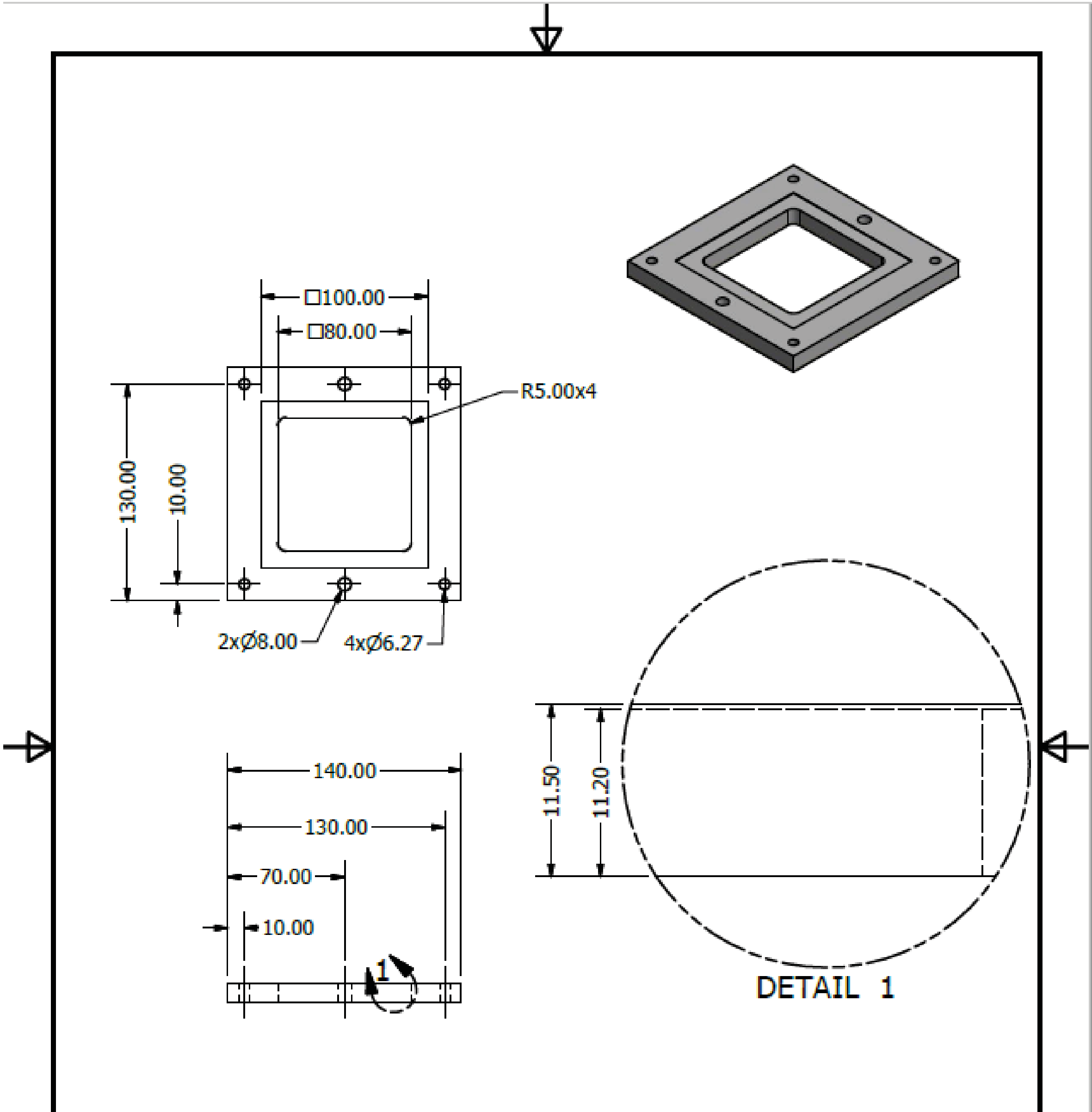
currency	MXN	Matriz		
APPROVED	R.P.S			
SI (mm)			DWG NO 6	REV
		SCALE 1 : 3	Size: A4	SHEET 1 OF 1



DRAWN Arturo Belmont	18/04/2018	UDLAP			
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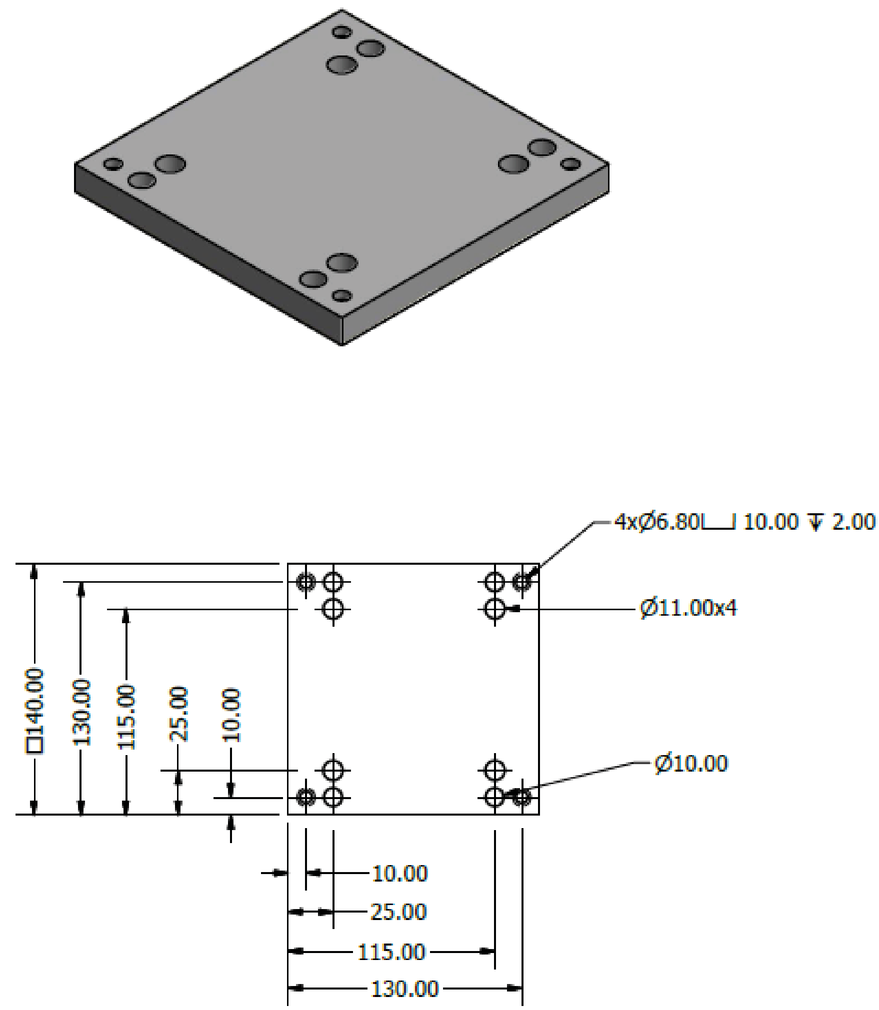

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currency	MXN		
APPROVED	R.P.S		
SI (mm)		DWG NO 8	REV
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