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Departamento de Engenharia Mecânica

Nelson Gil Monteiro Azevedo

Otimização de parâmetros de lubrificação e velocidade em SPIF

Optimizing lubrication and speed in SPIF processes

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Dissertação apresentada à Universidade de Aveiro para cumprimento dos requisitos necessários à obtenção do grau de Mestre em Engenharia Mecânica, realizada sob a orientação científica de Ricardo José Alves de Sousa, Professor Auxiliar com Agregação do Departamento de Engenharia Mecânica da Universidade de Aveiro.

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Palavras-chave

Estampagem incremental, ligas metálicas, ensaios experimentais, lubrificação, velocidade de conformação.

Resumo

Com a constante competitividade da indústria, existe a necessidade de criar novos métodos e processos que colmatem lacunas dos já existentes, assim como procurar soluções com rendimentos superiores, tanto quantitativamente como qualitativamente. A estampagem incremental surge aliada à dificuldade de produção de protótipos funcionais e reais. A necessidade de produção de pequenos lotes de peças a um custo competitivo é outro fator preponderante para a evolução deste tipo de tecnologia, visto que os métodos de estampagem tradicionais implicam custos muito elevados para a conceção das ferramentas necessárias. Esta tecnologia permite à indústria produzir uma grande variedade de produtos com custos reduzidos e numa janela de tempo bastante mais curta que a generalidade dos processos convencionais, o que torna a estampagem convencional numa tecnologia muito flexível proporcionando à industria uma vertente bastante interessante trazendo novas soluções para os vários tipos de mercado.

Neste trabalho, inserido no projeto SPIF-A (Single Point Incremental Forming at Aveiro) são estudados com recurso a testes experimentais, duas classes de parâmetros importantes quer para a qualidade, quer para o rendimento do processo: i) o efeito dos lubrificantes na qualidade superficial dos componentes produzidos e forças geradas durante a conformação e ii) o efeito do aumento da velocidade do punção conformador nas forças geradas e formabilidade das peças produzidas.

Face ao conhecimento gerado, considera-se que esta tese teve um contributo importante do desenvolvimento do processo de estampagem incremental com vista à sua melhor implementação industrial.

Keywords

Incremental forming, metalic alloys, experimental tests, lubrication, feedrate

Abstract

With the rising competitiveness in industry, it is mandatory to develop new methods and processes in order to fill some gaps, and at the same time ameliorate the existing ones. Incremental forming appears from the necessity to produce functional and usable prototypes, or alternatively, to produce small batches or replacement parts. In fact, the traditional use of press technology represents a very high cost when the number of parts in a batch is not big enough. Within incremental forming, the cost of tools is reduced to a minimum as just a punch and a clamping frame are needed to produce a part from the CAD model, which brings high interest to this technology.

This work is part of the SPIF-A project (Single Point Incremental Forming at Aveiro). From many possible parameters, focus will be given to lubrication and federate (the travel speed of the forming tool). These two parameters are utmost importance either for the quality of parts and for the process time efficiency.

After experimental tests, results will allow for conclusions that will certainly constitute a vital contribute for a better implementation of incremental forming processes into industrial environment.

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Introduction

For centuries, man has been producing sheet metal components using different tools and techniques. A method universally applied is the use of dies and punches, manufactured in accordance with the shape and dimensions of the component. However, despite being widespread, it contains technological hindrances, such as large energy costs and very high investment, which make this process very expensive.

On the other hand, the recent diversification in customers demand has resulted in the downsizing of the production quantities. Because of this reduction the cost of manufacturing tools needed to be reduced. This necessity gave origin to the intensification in the development of new production methods for a small lot. One of those methods is to create an incremental deformation in the sheet metal using a simple tool. The idea of incremental forming with a single tool, in the three Cartesian axes, was patented in 1967 by Leszak (1967). This method has later become very attractive, due to the advance of manufacturing technology in the fields of Numerical Control and Automation. With the massification of automation systems, like numerical control, incremental forming can now be fully automated and tends to be more available to general public. One of the great advantages of this method is the ability to use small and simple tools that create a deformation along a defined path. The tool can be a simple cylindrical metal tool , a laser beam, or a water jet. One of the techniques that is receiving great attention by the scientific community and from the industry is the Single Point Incremental Forming (SPIF).

In order to contribute to the better knowledge of the capabilities of this technology and since there are gaps in the bibliography, the work of this thesis aims to explore two of the main intervening parameters of the process, the lubrication and the feed rate, in the conformation of aluminum alloys and high strength steels.

Reading Guide

This thesis is divided in three chapters. The first one involves the definition of the incremental forming process and the detailed description of the different parameters that defines its quality and reliability. Also, it presents the state of art regarding the machinery used to perform SPIF operations.

The second chapter is focused on the study of lubrication parameters for incremental forming processes, from experimental testing carried out at the labs of University of Aveiro, and using the built SPIF-A machine.

Finally, the third chapter presents formability studies of aluminium and dual-phase steels regarding the variation of the feed-rate, that is, the travel speed of the punch across the sheet's surface. Experiments were also carried out using the SPIF-A machine.

Chapter 4 gives the thesis closure and conclusions.

Chapter 1: Introduction to incremental forming

1.1 Single Point Incremental Forming

Nowadays market demands to reduce manufacturing costs and design time results in more competitive solutions, which promote the development of new processes and technologies. In order to address the needs for flexible and small production batches, some innovative forming technologies emerged, such as the Single Point Incremental Forming (SPIF).

SPIF is an innovative process that has the capability of producing non-axisymmetric parts. It uses simple tools, usually a cylindrical metal tool with a flat or spherical tip (Figure 1). In this dieless process, a sheet is clamped without the need of any other kind of support, while the forming tool follows contours inwards, shaping the plate down gradually (Emmens et al., 2010). This eliminates the use of presses, because the forces involved in the process tend to be much smaller. Figure 1 shows the components involved for both SPIF and its variant, the Two Point Incremental Forming (TPIF)

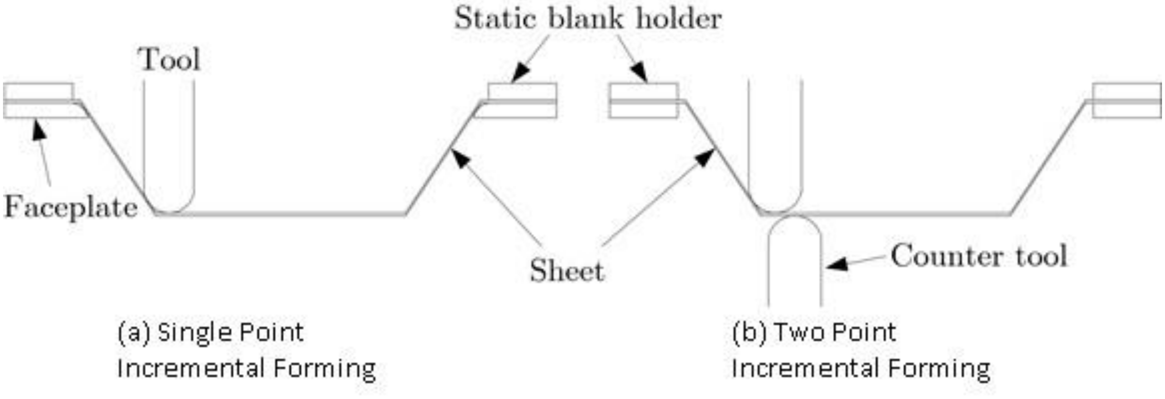

Figure 1 - Single and Two Point Incremental Forming main components (Alves de Sousa, 2016).

The deformation is performed by applying pressure on the surface of the sheet, forcing it to deform gradually. The metal sheet is usually restrained by the blankholder to avoid displacement and the flow of material into the forming area. Therefore, the whole forming operation is undertaken through the blank's thinning. The thickness of the blank at the end of the process may be related to the angle of the wall through the Sine Law, which implies that thickness will tend to zero if the wall angle is 90°. This fact constitutes one limitation of incremental forming processes.

The forming tool is controlled by CNC software and the path is predefined by a toolpath processor. This results in an enhancement in the precision when compared with processes that have direct human intervention.

Jeswiet et al. (2006) summarized the advantages and disadvantages of SPIF as follows:

Advantages:

- Useable parts can be formed directly from CAD data with a minimum of specialized tooling. These can be either Rapid Prototypes or small volume production runs.
- The process does not require either positive or negative dies, hence it is dieless. However, it does need a backing plate to create a clear change of angle at the sheet surface.
- Changes in part design sizes can be easily and quickly accommodated, giving a high degree of flexibility.
- Making metal usable Rapid Prototypes is normally difficult, but easy with this process.
- The deformation mechanism based on bending-stretch and the incremental nature of the process contributes to increased formability, making it easier to deform low formability sheets.
- A conventional CNC milling machine or lathe can be used for this process.
- The size of the part is limited only by the size of the machine. Forces do not increase because the contact zone and incremental step size remain small.
- The surface finish of the part can be improved.
- The operation is quiet and relatively noise free.

Drawbacks:

- The major disadvantage is the forming time that is much longer than competitive processes such as deep drawing.
- As a result, the process is limited to small size batch production.
- The forming of right angles cannot be done in one step, but requires a multi-step process.
- Springback occurs during the whole production phase, nowadays correction algorithms are being developed to deal with this problem (Meier et al., 2009).

1.2 Applications

Single Point Incremental Forming has a vast field of applications, such as aerospace, automobile, home appliances industry, marine industry and even fields such as medicine and food processing. It is a technology that is very versatile and can handle different kinds of materials, such as steel, aluminium, composite and polymeric materials. Figure 2 shows examples of the versatility in geometries that can be achieved using SPIF.

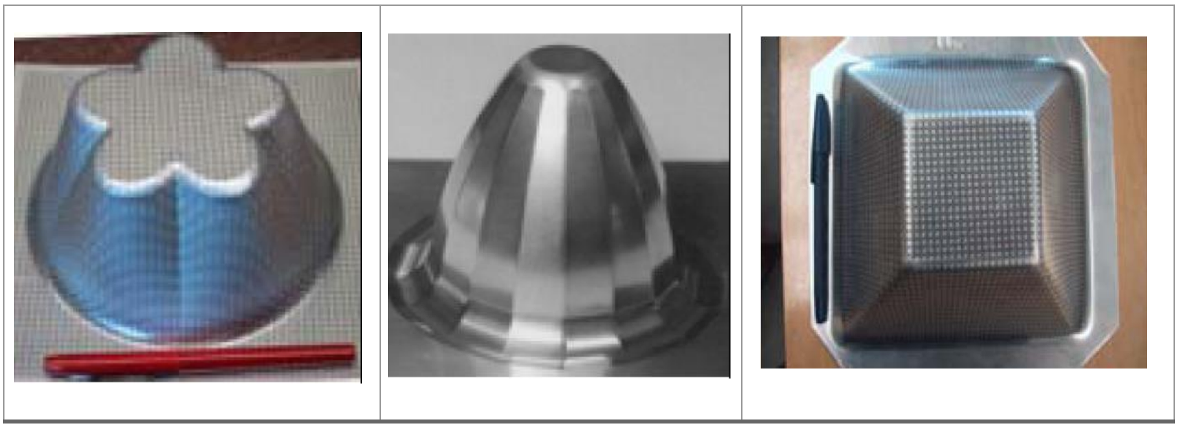

Figure 2: Different geometries achieved by SPIF, Five Lobe Shape, Faceted Cone, Truncated Pyramid (Jeswiet et al., 2005).

One of the major application areas of SPIF is in Rapid Prototyping because it has the capability of attaining functional parts. Given that, the car industry had its attention focused on this process because the field of application in areas like prototypes and replacement parts were vast and profitable. In the following figure, some examples where SPIF was used to make not only functional parts, but also tooling for other processes like hand layup or thermoforming (figure 3)

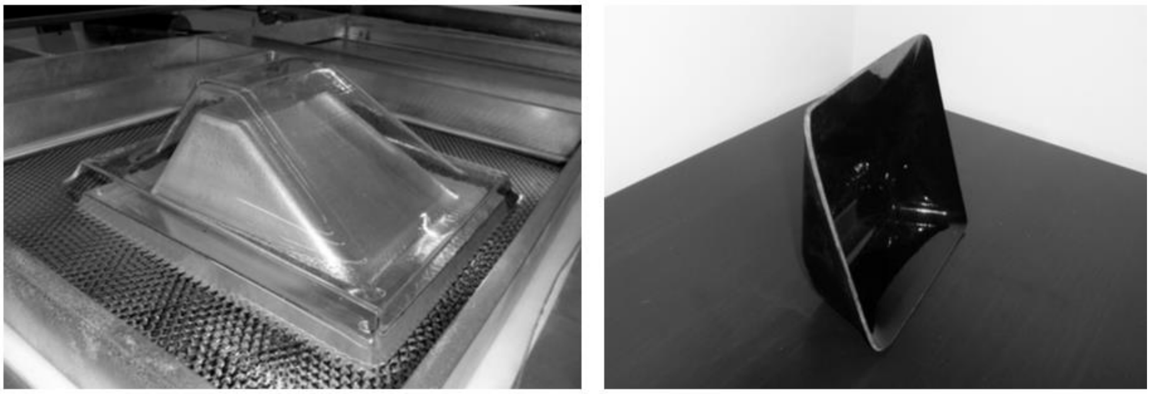

Figure 3: SPIF used as a rapid tooling facilitator for thermoforming (Afonso, 2017)

Another area where SPIF can have a great impact is in the medical industry, particularly in the manufacture of prostheses and braces. Using Reverse Engineering (RE) it is possible to reproduce high accurate models that replicate parts of a human body or support them.

For example, a cranial implant can be easily produced using SPIF (Duflou et al., 2005). The only necessary input is the CAD model, which can be obtained by lifting the form of the patient's skull. Then, this geometry is replicated in a metallic shell. An example can be seen in Figure 4.

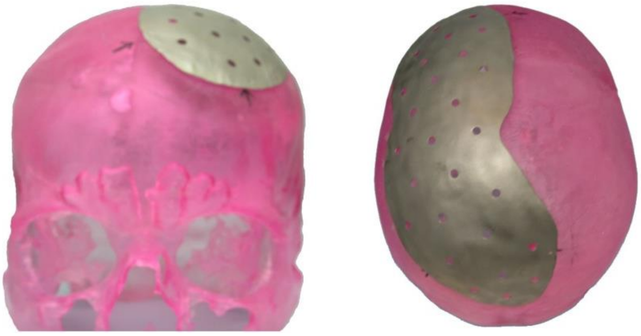

Figure 4 - Cranial implant obtained by incremental forming (Duflou et al. 2005).

Ambrogio et al. (2005) and Jeswiet et al. (2005) also addressed this field of application. Single Point Incremental Forming was used to produce a part that is used as an ankle support. The process began by using a contactless inspection, laser scanning, to obtain the morphological and dimensional information of the necessary body part in the form of a cloud of points. From this information, surfaces were made and ultimately a CAD model was built. Finally, via a CAD/CAM application, an ISO file was created and sent to a numerical control machine that carried out the Incremental Forming operation. Figure 5 demonstrates the different stages to manufacture the ankle support.

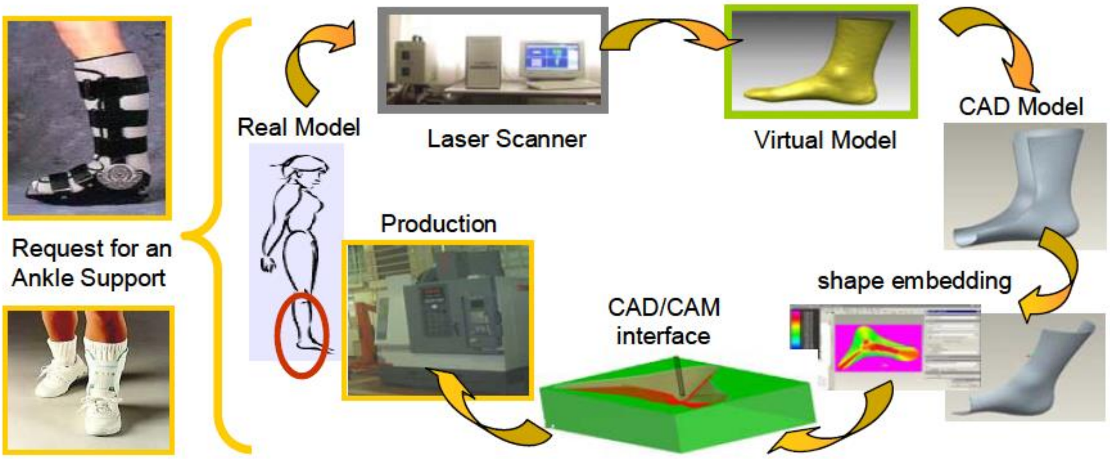

Figure 5 - The process of manufacturing an ankle support (Jeswiet et al., 2005).

1.3 SPIF Characteristics

1.3.1 Forming forces

One of the major characteristics that define a deformation process is the forming forces involved in it. According to Allwood et al. (2005), for SPIF process the forces involved in the process can be predicted using an approximate calculation by a theoretical model. They divided their analyses in two tool loading situations represented in Figure 6, (a) the tool travels normally to a flat sheet, causing a hemispherical indentation of the sheet; (b) during deformation, the tool moves horizontally ‘around’ the existing deformed area of sheet, creating a one-sided groove.

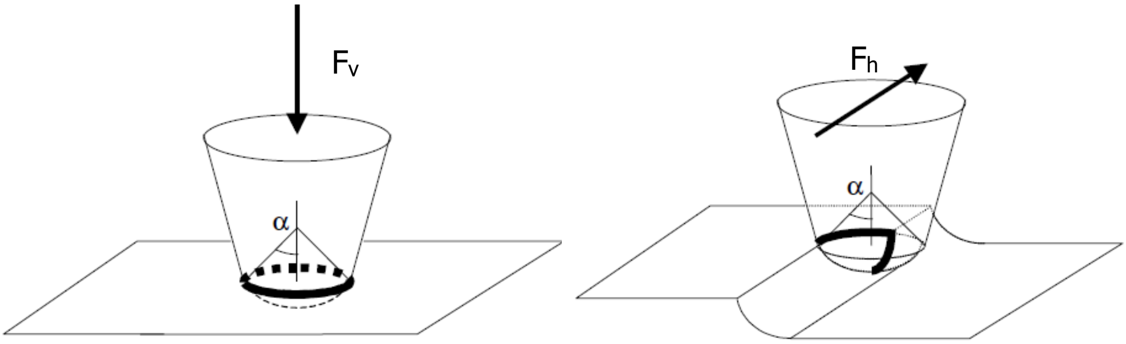

Figure 6 - Two tool load cases (Allwood et al., 2005).

With this theoretical model, a rough assessment of the forces can be made with some swiftness. For instance, a 1.6 mm thick mild steel, with a yield stress of $\sigma_y = 350\ Nmm^2$ and considering a tool radius of 15 mm, the predicted vertical and horizontal tool forces would be $F_v = 13.2\ kN$ and $F_h = 5.3\ kN$.

Various other authors developed experimental and numerical simulations in order to estimate the forces involved in the process (Duflou et al. 2005; Rauch et al. 2009; Jackson et al. 2008; Durante et al. 2008; Bouffioux et al. 2007), althougt the parameters between each analysis are significantly different. Aspects like different materials, blank thickness, tool diameter, step size and others were combined as the authors saw fit. For more detailed review of this subject please see Marabuto (2010).

1.3.2 Friction at the tool/sheet interface

One of the characteristics that is important in SPIF process is the interaction between the tool and the blank. This interaction can occur in different ways:

- The tool slides over the blank without rotation, but with a significant amount of friction.
- The tool rolls over the blank with its own rotation and with some friction.
- The tool rolls over the blank with free rotation and with low friction.

The control of the spindle speed allows the control of the friction between the tool and the blank during formation. Friction levels should be maintained low because friction generates heat causing surface degradation. According to Kim et al. (2002), the appearance of friction at the tool/sheet interface would result in the improvement of formability and delay of fracture occurrence. However, Kim et al. [15] also concluded that if the friction increased too much, the sheet would fracture.

As stated above, the existence of friction is beneficial to the formability. However, it also causes the sheet's surface degradation, therefore, in order to preserve the surface, lubricants are used. The absence of lubricants results in scratches on the sheet. Since products obtained by SPIF process are normally functional in its finished form, the state of the surface is an important theme, for that reason the use of lubricants are common and important. Another inconvenience due to the absence of lubricants is the increase of bending loads on the tool, which could result in misalignment or even fracture.
Doing so, one of the objectives of this work is to study the effect of lubricants, once such information is lacking in general in the literature.

1.3.3 Formability

One very interesting feature of SPIF is the increase in the material formability. Although the scientific community agrees that there is an increase of formability, compared with other processes like stamping or deep drawing, it is still not clear how the mode of deformation influences the formability of the process.

Some authors state that the deformation occurs by stretching, combined with bending, which promotes increased formability (Emmens et al., 2010). Other explanations are based on the presence of through thickness shear strain which leaded to the developments of extended Marciniak-Kuszinski models (Eyckens et al., 2009). Many experiments have been carried out and many more will be performed until a consensus is reached on this matter. However, the information already collected is very useful in giving insight on how the material will perform throughout the process. This topic is very interesting but it's out of the scope of this work.

1.4 SPIF Parameters

List of parameters that have really impact on SPIF conformation are material, sheet thickness, tool, feed rate, lubrification and conformation trajectory. The Feed rate and lubrication are discussed further in chapter 2 and 3.

1.4.1 Tools size and geometry

The tools normally used for SPIF have a spherical or a flat tip. This assures a continuous point contact between the sheet and forming tool. “Depending on the geometry and the material of the piece, the choice of the best tool can vary. In most instances, the ball-head tools are made out of steel, which is suitable for most applications. To reduce the friction, and to increase tool lifetime, the tool can be coated with or even made out cemented carbide.” (Jeswiet et al., 2005). An example of the different geometry and tool size can be seen in Figure 7.

A wide range of tool diameters can be used, from small diameters such as 6 mm, up to a large tool with 100 mm in diameter. These are normally used for the manufacturing of large parts such as car’s hoods, and require much more power because of the large contact angle involved. Depending of the size and the detail that we want to produce the choice of the tool generally are made by the rule of more detail less diameter.

Figure 7 - Coated tools (left), spherical tip tools (center), flat tip tools (right), from Jeswiet et al., 2005.

1.4.2 Incremental step-down size

Surface roughness is a major concern in a final product. Therefore, the quality of the product must be granted from the beginning of the process. In SPIF the major factor in determining surface roughness is the incremental step size, Δz. The surface roughness tends to increase, as the distance between the indentations caused by the displacement of the tool on the blank becomes greater. A representation of that occurrence is shown in Figure 8.

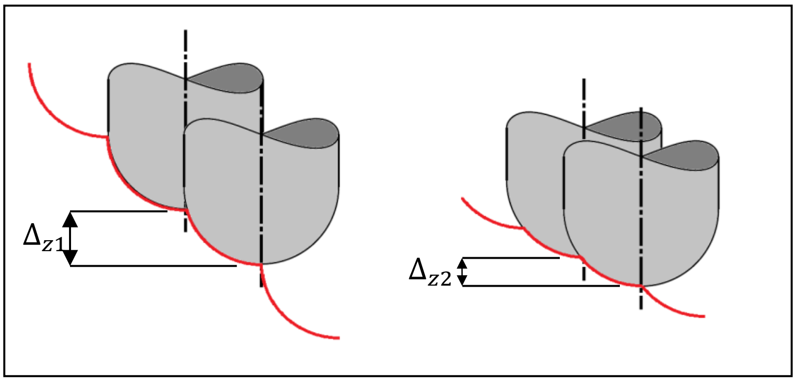

Figure 8 - Difference in surface roughness according to increase/decrease in step size.

An experiment conducted by Jeswiet et al. (2005) showed different surface roughness for different step-down sizes. This is a SPIF characteristic that needs to receive some attention, since the market is very demanding in terms of quality and because quality have a direct relation to the vertical increment, it becomes imperative to use small increments. Unfortunately a reduction in the step size can represent a significant increase in production time. Therefore, a balance must be sought between quality and production time. Figure 9 presents different surface finishes according to different step-down sizes.

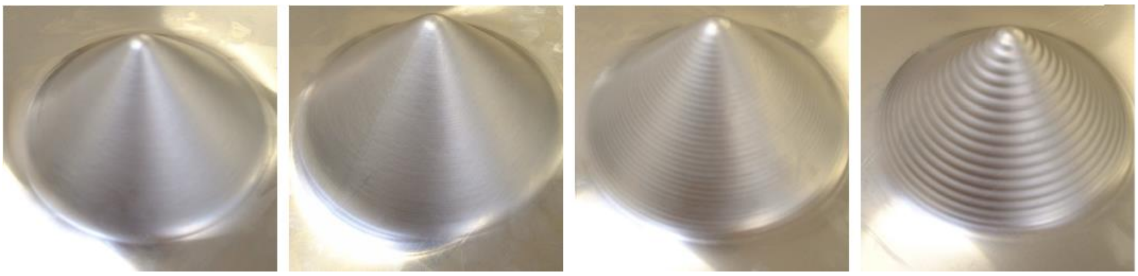

Figure 9 - A cone produced by the Cambridge ISF with varying step sizes. From left to right, 0.2 [mm], 1 [mm], 2 [mm], 4 [mm] (Allwood et al, 2005).

1.4.3 Materials

There is a constant development of the technology's, the methods to process materials and the own materials have also their own evolution.

With the rise of aerospace and biomedical applications, new materials have been created and others have seen their characteristics improved. In order to develop SPIF process, a number of materials have been tested. The more common used material is aluminium mainly because the machines where the tests are conducted have limitation in the maximum applicable force. Steel is target material for this process but do to the limitation mentioned above, only very thin sheets can the deformed. The list below summarizes, adapted from Marabuto (2010) some of the experiments made and the results/difficulties seen while testing different materials.

Table 1 – List of Materials tested by the authors and the results obtained (Marabuto, 2010).

Author	Material	Application	Characteristics
Ham et al. [16]	AA – 5754 AA – 6451 AA- 5182	–	Thickness: 0,8 – 1,5 mm
Jeswiet et al [2]	AA – 3003 O	–	Thickness: 0,93 – 2,1 mm
Micari et al. [17]	AA 1050 O	–	Thickness: 1,2 mm
Tanaka et al. [18]	pure titanium	denture plate	Main difficulties in the production of this part were the surface quality, needing to find optimal combination between feed rate and lubrication
Hussain et al. [19]	pure titanium	—	Proper tool, good lubricant and lubrication method were required
Jackson et al. [11]	sandwich panels	aircraft interiors, car body panels, architecture panels saving weight, absorbing sound, vibrations and impact, and isolating thermically	—
Franzen et al. [20]	PVC (Polyvinyl Chloride)	complex polymer sheet components with very high depths	—
Le et al. [21]	polypropylene (PP)	different geometries	—
Ji et al. [22]	Magnesium AZ31	structural applications	Warm temperatures

1.5 Incremental Forming Machinery

To perform Single Point Incremental Forming there are a few indispensable requirements. One of them is the need for a CNC-controlled three axis machines. Currently there are two ways to produce parts using Single Point Incremental Forming, adapted and dedicated machines. These machines may vary in type, but there are only a few dedicated models available, mainly because this is a recent technology and there are only a few companies that will invest in developing a SPIF machine. The most common is the use of adapted machinery. The characteristics that have to be accounted for SPIF work are speed, working volume, stiffness and load force. High speeds, large working volumes, sufficient stiffness and high load capacity are favorable. According to Jeswiet et al. (2005) the types of machines that can be used to do incremental forming are CNC milling machines, Robots, purpose built machines and Stewart platforms and Hexapods.

The more common in SPIF process is the use of three-axis CNC-controlled milling machines, which are adapted for the process (Figure 10), Duflou et al., (2005); Durante et al. (2008). According to Allwood et al. (2005) these machines are very attractive "because of the low additional costs of beginning operation". Unfortunately, they also have some disadvantages: firstly because "milling machines are generally not designed for high loads normal to the spindle, there is a danger that the machine will be damaged during incremental sheet forming operations". Therefore, the use of these systems is limited to softer materials, such as aluminium alloys, that normally involves forces applied to the tool much smaller when comparing to the forces needed for the steel. Secondly, "CNC machines do not generally provide instrumentation for measurement of three-axis forces at the tool tip". Third reason is that "the worktable of a CNC machine is generally solid and has limited width, so there is limited access to the reverse side of the workpiece", and also limits the work volume.

Since the simulation of SPIF process is complex and the time required to complete a simulation is currently many times greater than the times required to form the product, "high accuracy forming will only be achieved either by repeated trials of tool paths with correction based on errors in the finished form or by use of some form of on-line shape measurement and feedback control via an algorithm to modify the tool path".

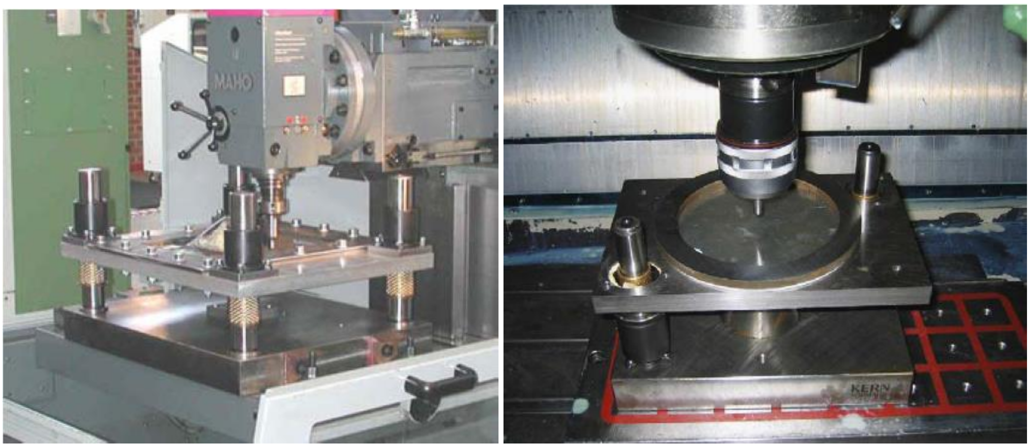

Figure 10 - SPIF adapted milling machines. (Left, Jeswiet et al. 2005), (right, Kopac and Kampus 2005).

Another technology that has been used/adapted in SPIF has been the robots with serial kinematics (Figure 11), Meier et al. (2005;2009). These systems are attractive because they have high flexibility and mobility which enables the manufacture of parts with high complexity and work at high speeds. The final position of the tool is the result of the combination of the different joint movements, which can occur at the same time. Another advantage is that they allow the tool to operate in the best angle configuration. This is an important aspect when dealing with complex shapes because it allows to nullify efforts that otherwise would be hazardous to the tool, and to the machine itself. It also prevents the degradation of the metal sheet and improves accessibility.

The disadvantages, like the milling machines, are their low stiffness and low admissible forces at the tip of the tools. Therefore, the use of these machines is limited to softer materials or else they would require investment in stiffening of the joints. Another disadvantage is the lower precision. Because it's a serial configuration, the positioning errors of the individual axes tend to sum and this result in higher geometric errors when comparing with other machines.

Figure 11 - Robot performing Single Point Incremental Forming (Duflou et al., 2005).

Finally, dedicated machines, unlike adapted machines, are designed for incremental forming process, and try to have simultaneously high rigidity and high flexibility. These systems allow the manufacturing of parts with complex geometries, while maintaining high accuracy and good surface finish.

Single Point Incremental Forming is in its early years. The means to perform this forming process are still very limited and rudimentary and there is not a satisfactory implementation level in the industry. There are very few models on the market, and a few currently being studied and proposed. Next section depicts the only commercial model of ISF machine on the market.

1.5.1 Amino Dieless NC Machine

The Amino Dieless NC Machine (Amino, 2015) is a technology developed by a Japanese company named Amino Corporation. They have developed a series of commercial models that work with the Two Point Incremental Forming principal. Their technology is based on a complete package that allows going straight from data to finished metal parts with only minimal soft tooling. According to the information available, the Dieless NC Machine can use a wide variety of materials, including mild steels, aluminium, titanium and even perforated steel mesh, with thickness ranging from 0.1 mm to 4.0 mm, depending on the model. The Dieless NC machine can be seen in Figure 12.

Figure 12 - Amino's Corporation, Dieless NC machine (Lamminem et al, 2005).

Amino Corporation offers standard sized models of their Dieless NC Machine. Two of the models, DLNC-RA and DLNC-RB, are designated as research-use and have smaller tables and slower in-table traverse speeds. The other 4 models, DLNC-PA, DLNC-PB, DLNC-PC and DLNC-PD, are primarily designed for industrial use. The specifications for all the models are shown in Table 2.

Table 2- Amino's Corporation models of the Dieless NC machine (Amino, 2015).

		DLNC-RA	DLNC-RB	DLNC-PA	DLNC-PB	DLNC-PC	DLNC-PD
Max. blank size (mm)		400x400	600x600	1100x900	1600x1300	2100x1450	2600x1830
Max. forming size (mm)		300x300	500x500	1000x800	1500x1200	2000x1300	2500x1750
Max. forming depth (mm)		150	250	300	400	500	600
Stroke (mm)	X axis	330	550	1100	1600	2100	2600
	Y axis	330	550	900	1300	1450	1900
	Z axis	200	300	350	450	550	650
Max. work holder size (mm)		700x750	1000x950	1300x1100	1800x1500	2300x1650	2800x2030
Forming capacity thickness (mm)	Steel (CR)	0.6~1.6	0.6~1.6	0.6~2.3	0.6~3.2	0.6~3.2	0.6~3.2
	Stainless	0.5~1.0	0.5~1.0	0.5~1.5	0.5~2.0	0.5~2.0	0.5~2.0
	Aluminum	0.5~3.0	0.5~3.0	0.5~4.0	0.5~5.0	0.5~5.0	0.5~5.0
Forming speed (m/min)	X, Y axis	30.0	30.0	60.0	60.0	60.0	60.0
	Z axis	310.0	10.0	10.0	10.0	10.0	10.0
AC servo motor power (kW)	X axis	0.9	1.4	5.9	8.2	10.0	16.0
	Y axis	0.9	1.4	4.5	4.5	4.5	7.0
	Z axis	0.9	0.9	1.0	1.0	1.0	3.0
Machine weight (ton)		3.0	5.0	6.0	8.0	10.0	(18)

In terms of operation, the Dieless NC forming is very similar to NC mills and machining centers. Simple to use software translates data directly into G-code tool paths. After having the G-code downloaded and being zeroed, the Dieless NC Machine then operates fully hands-free. As the spindle completes its path, the blank is lowered further over the fixture ready for the spindle to make another pass, continuing until the final shape is achieved. The volume of production can vary from a single piece, up to 500 pieces per month. The Dieless NC machine can even finish and assemble the part, performing actions as trimming, bending and hemming.

1.5.2 Cambridge ISF

In 2004, at Cambridge University, the Cambridge ISF (Allwood et al, 2005) was developed with the objective of performing SPIF operations (Figure 13).

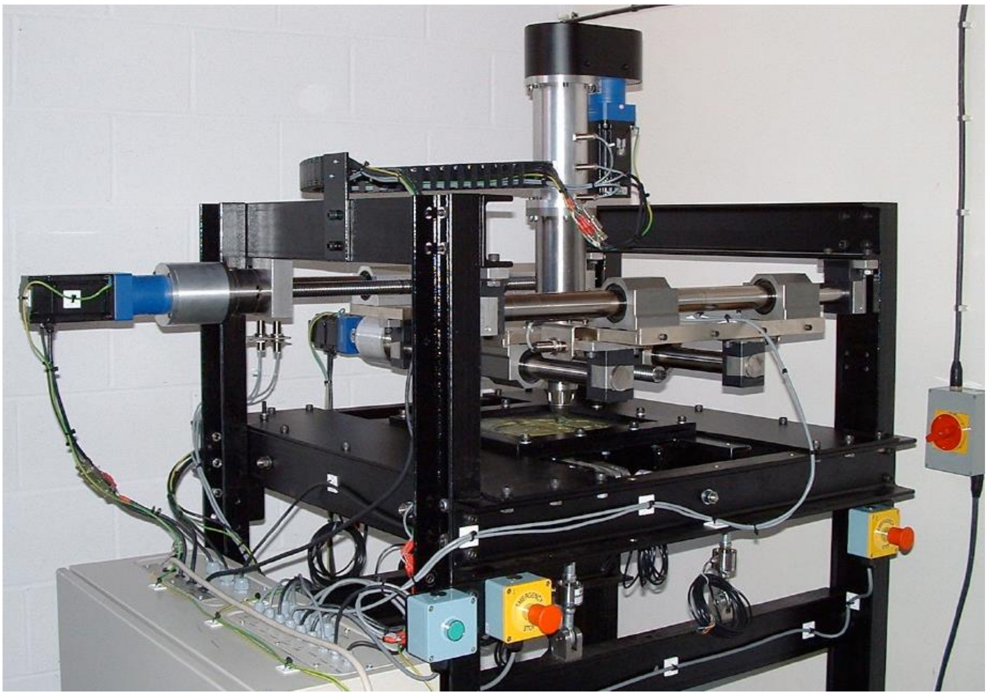

Figure 13 - Cambridge ISF Machine (Allwood et al, 2005).

According to Allwood et al. (2005), the development of this machine was centered on the distinctive requirement to maintain sufficient accuracy while in the presence of high horizontal and vertical tool forces. With that intent and to “avoid excessive moment loads on any of the bearing in the system, the vertical axis was maintained as close to the workpiece as possible. Vertical motion is controlled by a ball screw with a nut fixed to the tool shaft. The x and y axes are formed from two parallel hardened steel shafts, and are driven by ballscrews with co-axially mounted servo-motors driving the shaft via a planetary gearbox”. The rotation of the tool is freely sustained by bearings. A one-to-one gear drive is used to allow the motor to sit parallel to the main shaft. The specifications of the Cambridge ISF are summarized in Table 3.

Table 3 - Cambridge ISF Machine specifications.

Parameter	Measurement
Workpiece (active area)	300 x 300 [mm]
Material	Up to 1,6 [mm] mild steel
Vertical force	<13 [kN]
Horizontal force	<6,5 [kN]
Tool tip speed	<40 [mm/s]
Tool tip radius	5, 10, 15 [mm]
Maximum cone angle	67,5°
Maximum vertical axis travel	100 [mm]

The workpiece is held in a channel section frame, and may be clamped over a backing plate. The frame is mounted on six 10 kN load cells organized to provide a 6 degree-of freedom constraint without any moment loads on the load cells.

1.5.3 The SPIF-A machine at University of Aveiro

In order to make a positive contribution to the development of this industry and to the process itself, a new machine was developed at the University of Aveiro intending to take the potential of this process to the highest level. The project for such machine was initiated in 2010 in the work of Marabuto (2010). The final version is published in Alves de Sousa et al. (2014).

This machine brings a new approach to the SPIF industry, once machinery used to perform SPIF operations has limitations in their work volume with limited movements and in the magnitude of applicable forces. With that in mind, this machine was projected to overcome that obstacle, and was provided with a system with 6 degrees of freedom, while maintaining the ability to apply high loads. The disadvantage is the increase in volume occupied by the kinematic system.

This project and consequently the machine have received the name of SPIF-A. SPIF stands for Single Point Incremental Forming and the A stands for Aveiro, since this project is being carried out at the Department of Mechanical Engineering of the University of Aveiro.

The machine was designed to withstand at least the force requirements as proposed in Allwood et al (2005), but it can withstand up to 20kN of compressive forces and 13.5kN lateral ones. The complex real-time control of toolpath is ensured by a Simulink (MatLab) environment as developed by Bastos (2014).

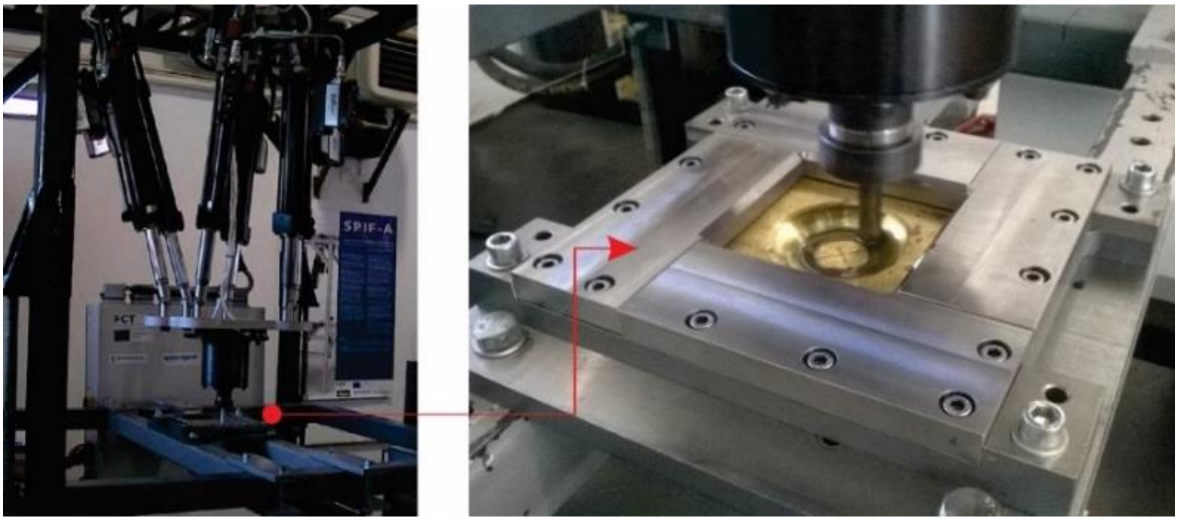

Figure 14: The SPIFA machine: left) kinematic system; right) forming table

Chapter 2: Lubrication aspects in incremental forming

2.1 Introduction

Single Point Incremental Forming has shown to promote higher formability when compared to deep drawing for instance, given its localized deformation that prevents necking. The SPIF technology provides significant benefits to manufacture small batches and prototypes, once it is not necessary to spend time and money in tooling. However, because of its particularities, the process is still not fully understood, mainly regarding springback that affect the dimensional accuracy of the formed parts, the forces involved and the deformation mechanism. The first approach to circumvent these problems is to adjust the tool path. Another possibility is to vary the tool diameter, the value of the vertical increments or even the tool travel speed. Concerning surface finish and forming forces, it is crucial to study the influence of lubrication in this process. Even if many developments have been carried out in the field of incremental sheet forming, there are still few studies on the influence of lubrication on the surface quality of the final product and on the resulting forming forces. The use of lubricants is essential in the interface between two or more components of most mechanisms and on any forming process, giving tooling a longer life by reducing friction and wear, improving heat distribution and removing waste materials.

Friction evaluation during most classical (press-forming) sheet metal forming operations can be a very complex task as documented in Figueiredo et al. (2011). Tisza and Fülöp (2001) classified friction tests for sheet metal forming as a function of the main performed operations such as stretch forming, deep drawing or stretch drawing.

However, it is well accepted that during incremental forming process, deformation mechanisms and forces involved considerably differ from, for instance, press stamping deformation mechanisms, with increased formability (Emmens et al., 2010; Silva et al., 2008; Micari et al., 2007; Filice et al. 2002; Fratini et al. 2004). Even so, there is not much discussion in literature about such differences and its impact on lubricant choice.

Hussain et al. (2008) studied the applicability of various lubricants in incremental forming of pure titanium. Zhang et al. (2010) analyzed the effect of lubrication in the hot forming of magnesium alloy finding that a solid graphite or ceramic powder (MoS2) delivers outstanding results, as well as a self-lubricating effect. For soft metals such as aluminium and low carbon steel, mineral oils will suffice to produce components with an acceptable surface quality (Kim & Park, 2002). On the other hand, solid lubricants are very effective due to their wide temperature range, from room temperature to circa 400 °C. However, they are generally coated with a binder on the workpiece by conventional spraying, which adversely affect their characteristics and life span (Hanada et al., 2005). Finally, in a master thesis carried in University of Porto (Suriyaprakan, 2013) AS-40 grease was employed in SPIF yielding good results.

In the remaining incremental forming studies, the use of lubricant in tests is just referred without ever describing its type or its influence on the obtained results. It is clearly evident that there is a gap about the role played by the lubricant in the forming process. In this work, several lubricants will be tested on what concerns the surface finish obtained using SPIF technology, and for two different materials: Steel (DP780) and Aluminium (AA1050-T4).

2.2 Experimental Methodology

2.2.1 Lubricants and metal sheets

There is high number of different lubricant brands, and a number of distinct products with different characteristics, like viscosity and density. At this work, it was tried to cover (keeping a reasonable number of tests on the experimental campaign) the various different possibilities, choosing three greases/pastes and two oils that, despite being both of mineral origin, contain very distinct viscosity properties. The properties of the selected lubricants are described in Tables 3 and 4.

Table 3 - List of lubricants studied

Lubricant	Type	Viscosity at 40ºC [mm²/s]	Density [kg/l]	Melting Point [ºC]
Repsol SAE 30	Mineral Oil	105	0.884	215
Total Finarol B 5746	Mineral Oil	9.75	0.904	150
Moly Slip AS 40	Paste		1.76	190
Weicon AL-M (allround)	Paste	185	0.92	
Moly Slip HSB (high speed bearing)	Paste	N/A	N/A	195

Table 4: List of lubricants (greases) studied

Lubricant	Base	Solid Lubricant
Moly Slip AS 40	Petroleum oil	MoS2 (40%)
Weicon AL-M (allround)	Mineral oil	MoS2/Li
Moly Slip HSB (high speed bearing)	Lithium	MoS2/Molysplip special/ E.P compounds (9%)

Figure 15: Range of lubricants used

On sheet's materials side, a major amount of research carried out in incremental forming uses aluminium or steel sheets. In this work, 1mm thick sheets of 1050 aluminium series and high strength dual phase steel DP 780 were used, representing soft and hard materials, with mechanical properties described in Table 5.

Table 5: Sheet's material

Material	Density [g/cm^3]	Young Modulus [MPa]	Tensile Yield Stress [MPa]	Hardness [HV]
Aluminium AA1050	2.7	70000	250	40
Steel DP780	7.8	210000	780	258

2.3 Incremental forming machine

The SPIF-A (“A” named after Aveiro) developed and built through a new concept of incremental forming machine based on parallel kinematics, compared to the machines presented at the state-of-art section, represents an improvement over adapted NC milling machines and serial kinematics robot arms, as possessing higher structural stiffness, low inertia and 6 degrees of freedom thanks to a custom-built Stewart platform (Alves de Sousa et al., 2014). The machine was designed to support compressive and lateral loads of 13kN and 6.5kN respectively, with a working area of 1000mm x 1000mm and a maximum vertical displacement of 400mm. The kinematic system implemented in SPIF-A, is presented in Figure 16.

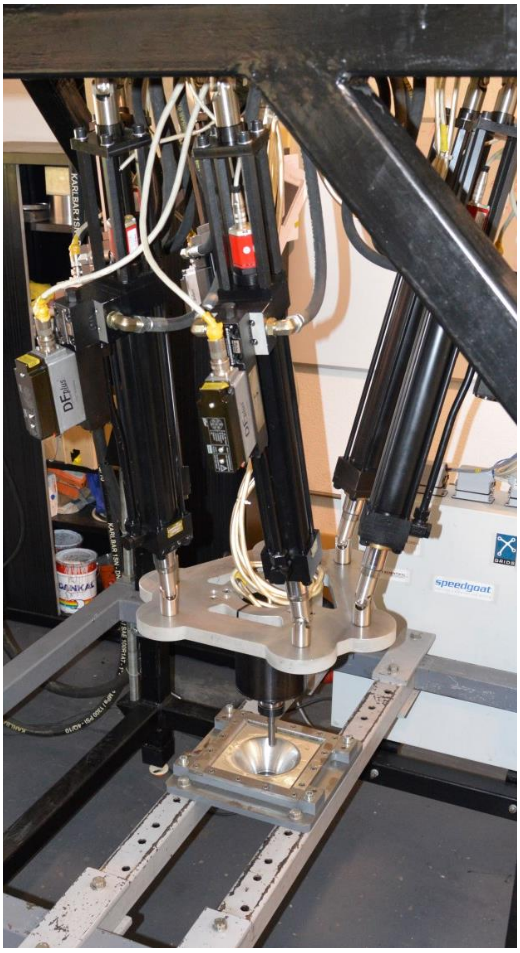

Figure 16: SPIFA incremental forming machine.

2.4 Tests

The tests consisted in incrementally forming truncated cones, 20mm deep, diameter 60mm and wall angle of 45°. Other more complex geometries were studied but were discarded in favor of the cone, due to its simplicity, faster execution time and more straightforward analysis. Figure 17 illustrates the geometries produced.

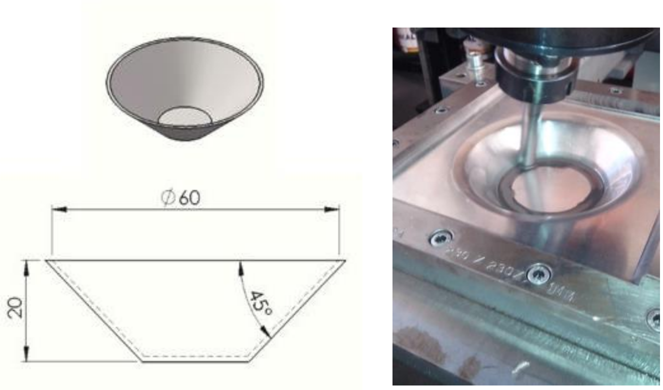

Figure 17: Incremental formed conical parts.

The tool used in the experiments is made from cold working steel (X210CrW12) which according to Jeswiet et. al. (2005), is a suitable material for most SPIF applications. The tool was also heat treated, resulting in an increased hardness to 58HRc. Its geometry, consisting on a spherical tip with a 6 mm radius can be seen in figure 18.

The trajectory performed by the tool consists of spirals with a vertical increment of 0.3 mm and a control Scallop 0.1 mm. This type of tool path allows continuous vertical increment along the geometry of the part, thus preventing the occurrence of peak forces. The feed rate used is 1000 mm/min.

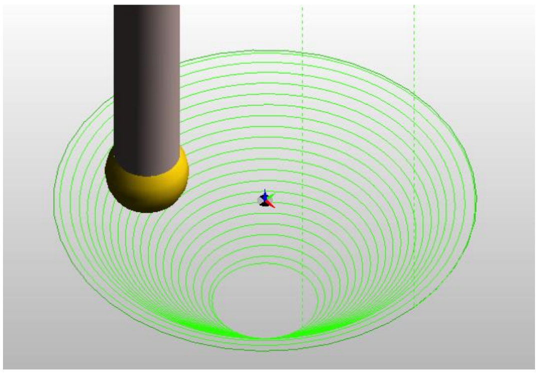

Figure 18: Simplified scheme for tool and toolpath

2.5 Roughness measurement

In all tests, the lubricant was applied directly on the sheet surface right in the beginning of the forming process. In fact, a small amount of lubricant is required when the sheet is placed horizontally as in SPIF-A case. The lubricant follows naturally by gravity the toolpath during the whole forming process. After forming and unclamping, roughness tests were conducted using an electromechanical Hommelwerke T1000 rugosimeter (Figure 19).

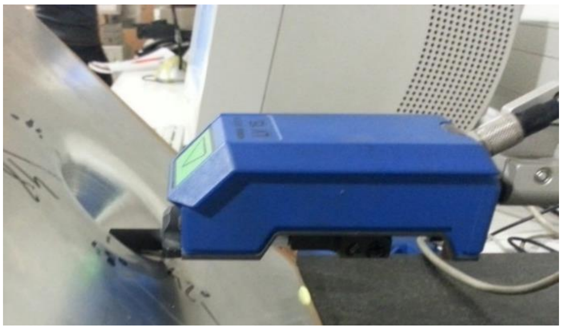

Figure 19: Measuring surface roughness.

A support was created to ensure the parallelism of the wall and the fixed rugosimeter's needle. Each piece went through 8 roughness tests at intervals of 45 ° around its center line. In fact, due to material anisotropy it is possible to detect different material flows on the formed cone wall (Figure 20), with distinct stretching conditions. However, such differences proved to not having a direct influence on the final roughness.

Figure 20: Example of the effect of material anisotropy on a formed truncated cone.

2.6 Results and discussion - Roughness

Standard roughness parameters were analyzed for each lubricant. Parameters measured according to DIN4768 standard were the arithmetic mean roughness (Ra), the total height of the roughness profile (Rt) and the mean roughness depth (RzD). Results are summarized on Table 6.

For 1050 aluminium, tests point out that the SAE30 oil yields the best surface finish, with the AL-M also showing good results, with the lowest value in Rt. Tests performed with Finarol B5746 presented high roughness across the surface, inclusive impairing the realization of roughness tests. Figure 21 shows the best (smoother) and worst (rougher) finished surfaces obtained with aluminium sheets for different lubricants.

Table 6: Average roughness values for aluminium 1050.

Lubricant	Ra [µm]	RzD [µm]	Rt [µm]
AL-M	0,995	4,955	7,014
AS-40	1,128	5,672	7,492
HSB	1,043	5,275	8,672
SAE 30	0,873	4,417	7,485
Finarol B5746	-	-	-

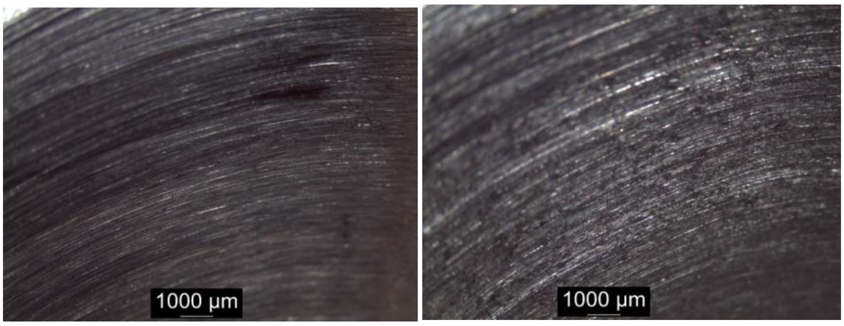

Figure 21: Surface quality of formed 1050 aluminium cones for lubricants SAE 30 and Finarol B5746, respectively.

Table 7 shows the roughness values achieved after forming DP780 steel parts. Oppositely to AA1050, Finarol B5746 delivered the smoothest roughness, with AS-40 grease giving very similar values. In this case the SAE 30 is the lubricant that produces the worst level of surface roughness. Both the smoother and rougher results can be checked in Figure 22.

Table 7: Average roughness values for DP 780 Steel.

Lubricant	Ra [µm]	RzD [µm]	Rt [µm]
AL-M	0,368	1,850	2,490
AS-40	0,215	1,285	1,910
HSB	0,295	1,788	2,415
SAE30	0,473	2,688	4,405
Finarol	0,210	1,230	2,055

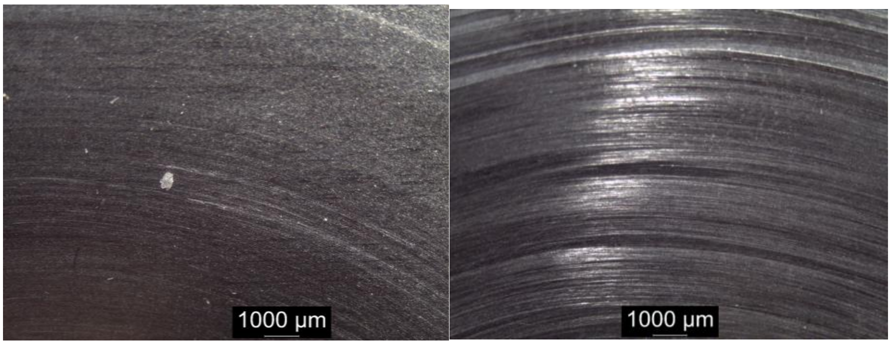

Figure 22: Surface quality of formed DP 780 steel cones for lubricants Finarol B5746 and SAE 30, respectively.

According to the results, there is an apparent relation between the lubricant viscosity and the formed material hardness in what concerns the surface finish quality. For softer materials, a lubricant with high viscosity provides better results in the final surface. On an opposite trend, for harder materials, such as DP780 steel, lubricants with lower viscosity values provide best finished products. In other words, lubricants most appropriate for use in incremental forming of aluminium won't produce good results when forming steel, and vice-versa. Solid lubricants (like MoS2) didn't bring significant advantages, once the obtained surface finish is quite similar to the one achieved with low viscosity mineral oil, a much cheaper product.

2.7 Results and discussion - Forming forces

In any forming process, it is desirable to minimize the amount of forces involved to produce a given part. To support the conclusions related to lubricant effects, in this session the effect on forming forces is studied. While the tool described the desired forming trajectory, radial and compressive forces were recorded for AA1050 (represented in figure 23), and DP780 (figure 24).

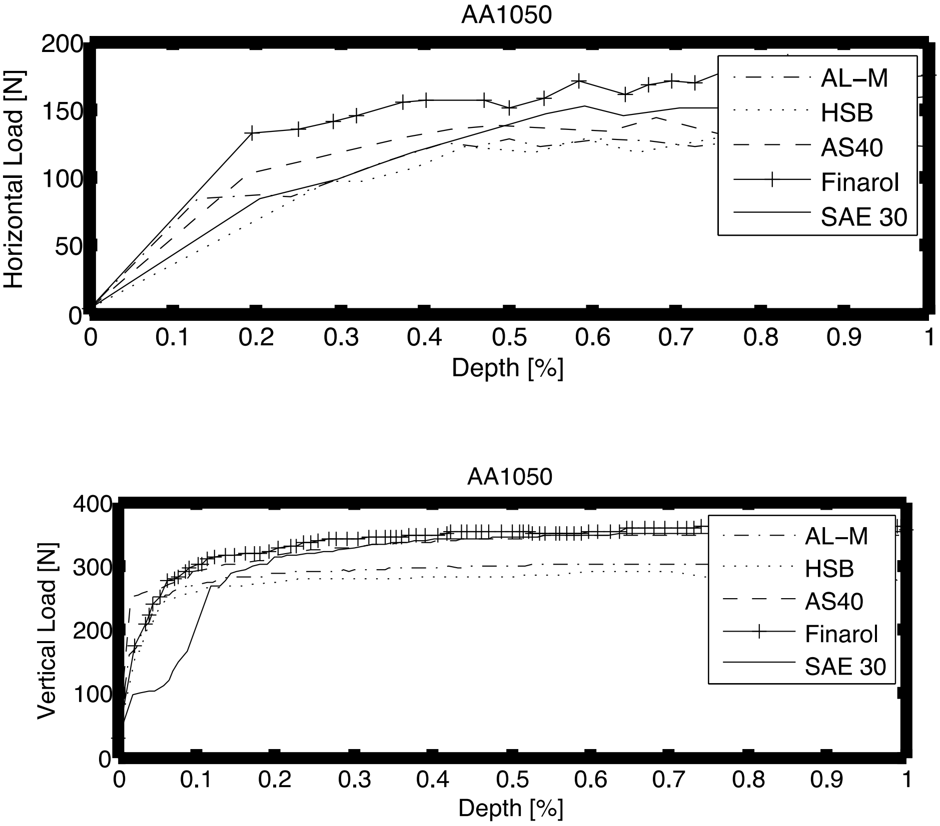

Figure 23: Distribution of vertical and horizontal Forces (in Newton) as a function of forming time (in percentage value) for AA1050.

From the analysis of Figure 23, it can be seen that HSB and AL-M lubricants yields similar vertical forces. The same behavior was observed for AS-40, Finarol and SAE 30. Two levels of vertical (compressive) forces were observed, circa 280N and 330N. The first level corresponds to the tests with the HSB and AL-M lubricants, and the other for the remaining lubricants. Regarding to horizontal (radial) forces, the highest value was approximately 170N and the lowest around 120N. It was also noted that the application of Finarol B 5746 corresponded to the highest forces in both directions, and the worst finish. The curve trends were quite similar, and generally lubricants giving larger vertical forces are also those with higher horizontal forces. However, a direct relation between forming forces suffered and final quality of the surfaces cannot be deduced, since the test with SAE 30 presented good surface finish but high force values (similar to the rougher case, the Finarol lubricant). Distinguishing types of lubricants (oils and pastes) wasn't possible, because the AS-40 grease featured compatible force values compared to those measured when testing the mineral oils.

Figure 24 depicts forces sustained by the tool when forming DP780 dual phase steel, and as would be expected, the forming force values were much higher than for aluminium.

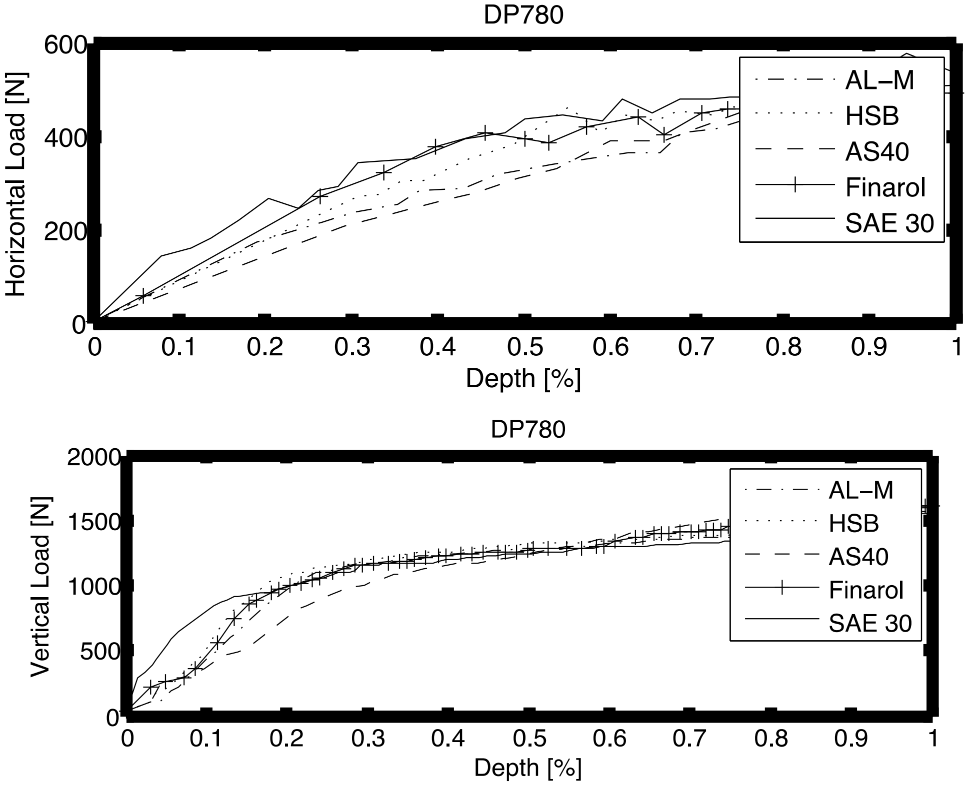

Figure 24: Distribution of vertical and horizontal Forces (in Newton) as a function of forming time (in percentage value) for DP 780 steel.

The trend of the force curves for steel and aluminium are quite alike, differing only in magnitude. For the case of steel, the forming forces for different lubricants show no relevant differences, specially vertical forces tending to 1500N and showing slower growth from 1100 N. Horizontal forces grow more monotonically over time. Similarly to the aluminium, it is difficult to identify any relation between the distribution of forces, the type of lubricant used and surface quality achieved. Again, the lubricants with better results in terms of surface finish (AS-40 and B5746 Finarol) show horizontal forces values situated on the lower and higher force value bounds. Finally, as typical from SPIF operations, for both materials, vertical forces are approximately two times greater than the horizontal ones (Allwood et al., 2005).

2.8 Conclusions

This study allowed establishing some conclusions about the used lubricant relevance during the single point incremental forming process. Indeed, under a same given set of forming parameters, it indeed influences the final surface quality of the parts obtained. Even if the machine, the toolpath strategy and the geometry to obtain are the most influencing parameters, the use of a suitable lubricant may significantly improve the surface finish quality, reduce forming forces and prevent tool wear.

From the results obtained, some conclusions are straightforward. SAE 30 oil and AL-M grease provided better results for AA1050 sheet parts, while Finarol B5746 oil and AS-40 grease distinguished themselves in forming DP780 steel. According to the results obtained, it was possible to find a clear relation between the hardness of the material to form and the viscosity of the lubricant used on the final roughness. The greater the hardness of the material to form, the lower the necessary viscosity. Concerning greases, it can be concluded that they generally provide a good finish, even though in this case they haven't particularly stood out when compared with the oils used.
Additionally, there seems to be a relation between the necessary forming forces and the surface finish quality. As expected, the forces required to process DP780 are significantly higher, and generally result in a better finish, when compared to aluminium parts. There is a clear relation between the level of compressive forming forces, the hardness of the material and the surface finish itself, for a given set of incremental forming parameters used.

Analyzing the values of the resulting radial and compressive forces for each lubricant for each material studied, it can't establish any direct relation of interest, once similar finishes implied different resultant forces. Naturally, the lubricant requiring less forming forces would be the most indicated to perform SPIF.

Chapter 3: : Feed rate influence in incremental forming

3.1 Introduction

In this chapter, focus is given on the effect of increasing tool travel velocity. To this end, a dedicated SPIF machine is employed. After forming steel and aluminium sheets, parameters like forming force, geometrical accuracy and formability are assessed for a range of velocities from 1500 to 12000 mm/min. Parameters like step down or tool diameters are kept constant for a clear comparison. It will be shown how the process can be fastened up without seriously compromising the process feasibility.

Some effort has been devoted to study the influence of feed rate in the process feasibility. Ambrogio et al. (2012; 2013) or Hamilton and Jeswiet (2010) studied the effect in terms of shape accuracy and surface roughness, concluding for instance that aluminium material keeps formability properties unchanged with feed rate variation (Ambrogio et al. 2012) and for Titanium Ti6Al4V, hardness and microstructure also seem to remain practically unaffected (Ambrogio et al. 2013). In both works, A CNC lathe was used to promote very high feed rates, but naturally at the expense of reducing the range of geometric possibilities within the SPIF process. Hamilton and Jeswiet (2010) formed 0.8 thick 3000 series aluminium at feed rates ranging from (5080 to 8890 mm/min) and analysed roughness and thickness distribution. Here, conclusion point to the possibility of grain refinement and consequently formability improvement.

In this chapter, feed rate will range from 1500 and 12000 mm/min. The contribution to the state-of-art will be given by analysing not only aluminium material (for the sake of comparison against the cited works) but also high-strength steels, namely dual-phase ones, the same used in the other study. The authors understand that analysing this kind of material have importance in the context of possible market applications, like in automotive industry. Furthermore, the chosen materials allow the production of asymmetric parts within the range of speed proposed. Formability and processing forces will be analysed in the forthcoming sections.

3.2 Experimental Tests

The so-called SPIF-A machine provides large payload (20kN) and flexibility driven by a 5 degrees-of-freedom hydraulic Stewart platform on the kinematic side. A sixth degree of freedom would be the drilling one, but the tool was chosen to behave passively, driven by friction forces only. Actuators are from hydraulic nature and controlling strategy is based on real-time machine (Bastos, 2014) using Matlab/Simulink which has been allowing to perform the process using moderately high speed and 5-axis tool-path strategies.

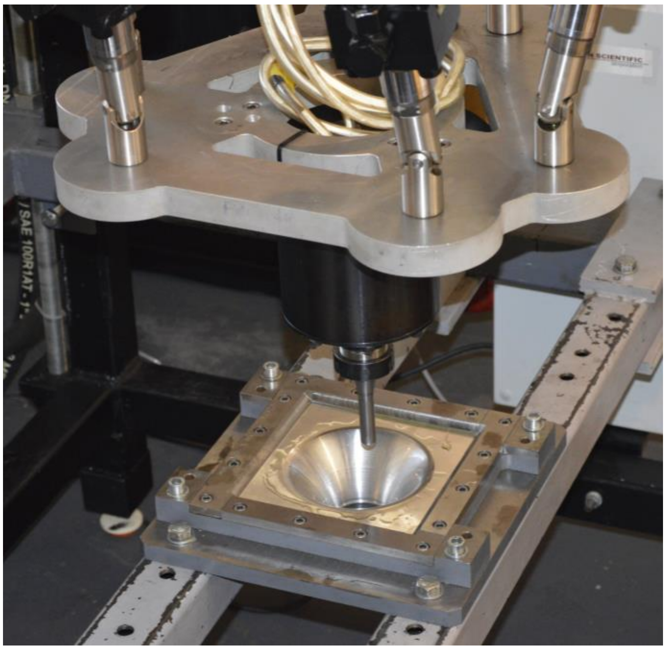

Figure 25: Forming table of SPIF-A Machine

To evaluate the effects of tool tip velocity the frustrum of a cone geometry was considered, figure 26, Hussain et al, (2012). This continuously varying-wall-angle geometry allows obtaining a clear comparison of forming forces, being additionally a very popular example to evaluate formability in terms of maximum wall angle. Complementarily, the sheets were grid-marked by electrochemical etching (Universal Marking Systems), which permitted to plot the fracture forming line for different feed rates.

Two different materials were analyzed. Aluminium, 1050 series, and Dual-phase steel in three different grades, DP600, DP780 and DP1000. Apart from aluminium, these materials were hardly tested up to date given the lack of SPIF machinery to withstand large forming forces. To keep the number of experiments at a reasonable number, several parameters need to be fixed for a clear comparison, as listed in Table 8.

Table 8: Fixed parameters during experiments

Tool tip diameter: 16 mm
Sheet thickness: 1mm
Lubricant: SAE 40 oil
Tool path strategy: 3 axis helical, 0.5mm step down

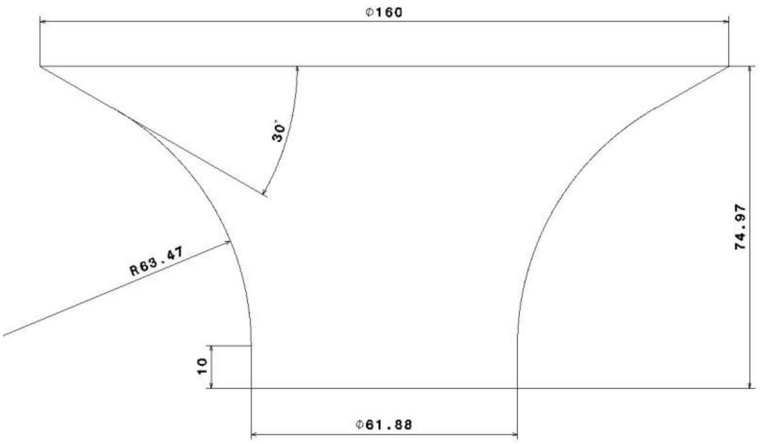

Figure 26: Frustrum of cone geometry

Bearing in mind the previously referred fixed experimental variables, a set of 4 different velocities was defined as in Table 9. Velocity 1 can be considered extremely slow, and serves to establish a reference result where no effects of feed rate may be observable. Velocity 4 can be considered sufficiently fast to produce SPIF parts in a pace compatible with industrial needs. Such values are compatible with production of non-asymmetric arts by the SPIF-A, although not being the case in study. Doing so, forming time can be reduced 5-6 times from velocity 1 to velocity 4, as shown at the bar graphics in figure 27.

Intermediate feed rates 2 and 3 will serve the purpose of establishing a trend for the results.

Table 9: Forming Velocities

Nomenclature	Velocity [mm/min]
Vel. 1	1500
Vel. 2	2500
Vel. 3	3500
Vel. 4	12000

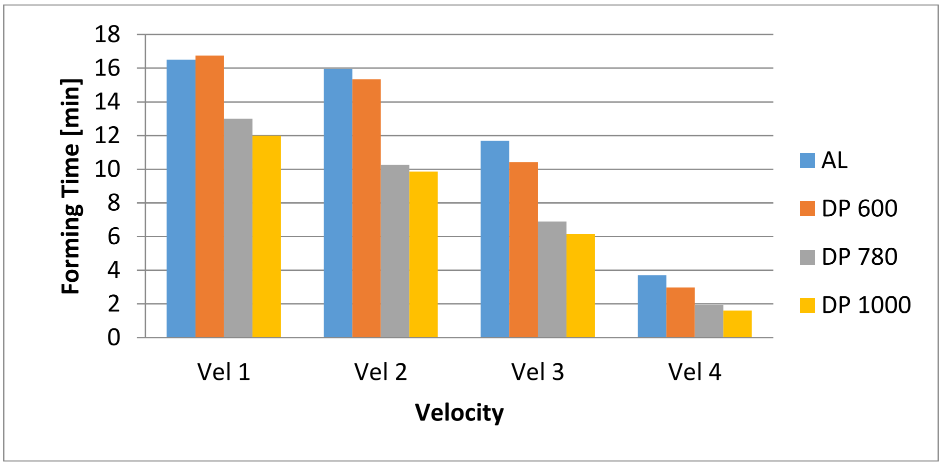

Figure 27: Forming times regarding feed rate. Frustrum geometry depth can vary depending on the material employed.

Figure 28: Aluminium Frustums - Vel.1 Vel.2 Vel.3 Vel.4 (Right to Left)

Figure 29: DP600 Frustums - Vel.1, Vel.2, Vel.3, Vel.4 (Right to Left)

In the first impressions it is possible to verify that the aluminum behavior is quite different from the DP steel, figure 28 and 29, analyzing the final geometry of the conformation. It is possible to verify that the conformation time greatly reduces with increasing speed, comparing the final results of the aluminum and the time used for each velocity. In the case of DP steels, the conformation time limitation is due to the fracture of the material, so these conformation time is lower when compared to a material (AL) that can practically execute the geometry in its entirety.

3.3 Results

3.3.1 Forming Forces

The first set of results to be analysed are the forming forces. The SPIF-A machine is equipped with 3 load cells embodied at the tool holder. Vertical (compressive) and lateral (radial) forces were continuously recorded during forming process (Figures 30 to 33). As expected for the SPIF process, compressive forces are generally 3-times higher than lateral ones (Alwood et al, 2005. Recorded peak compressive forces are circa 470N for aluminium and 2600N, 3700N and 4300N for DP600, 780 and 1000 respectively, which is in accordance the materials mechanical resistance.

Concerning aluminium 1050-H111 (Figure 30), it is interesting to note that compressive forming forces increase very clearly from the beginning of the manufacturing process until 50% of depth, then decreasing until necking takes places at the cone wall with subsequent fracture. The effect of velocity on compressive forces appear to be not very significant (about 10% variation) leading to a quicker increase of forces until the force peak and then to an also quicker force value decrease until failure. Regarding radial forces, the evolution is positive practically until the end of forming (85-90% depth), then decreasing due to necking. Furthermore, the effect of feed rate is only moderately pronounced at the last forming stages (70-100% depth), with the lower feed rate yielding lower forces.

Analysing the results of dual-phase steels (Figures 31 to 33), it is possible to check the positive evolution of compressive forces up to 35-40% of forming depth, followed by a sudden decrease at the final forming stages due to necking. Radial forces have a more smooth increase during the whole manufacturing process. If one analysis the evolution of forces from 0 to 85% forming depth, before the onset of material stability, it is possible to check that the influence of feed rate on force values is kept always limited to circa 5-10%, which suggests for the range of velocities studied (up to 15m/min) the effect on forming forces is perfectly acceptable for parts production.

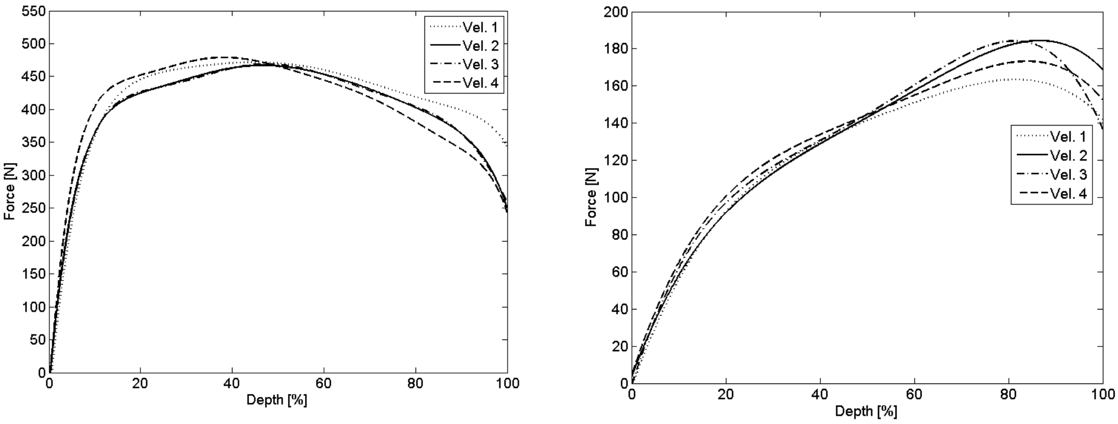

Figure 30: a) Vertical Force – Aluminium **b) Radial Force – Aluminium**

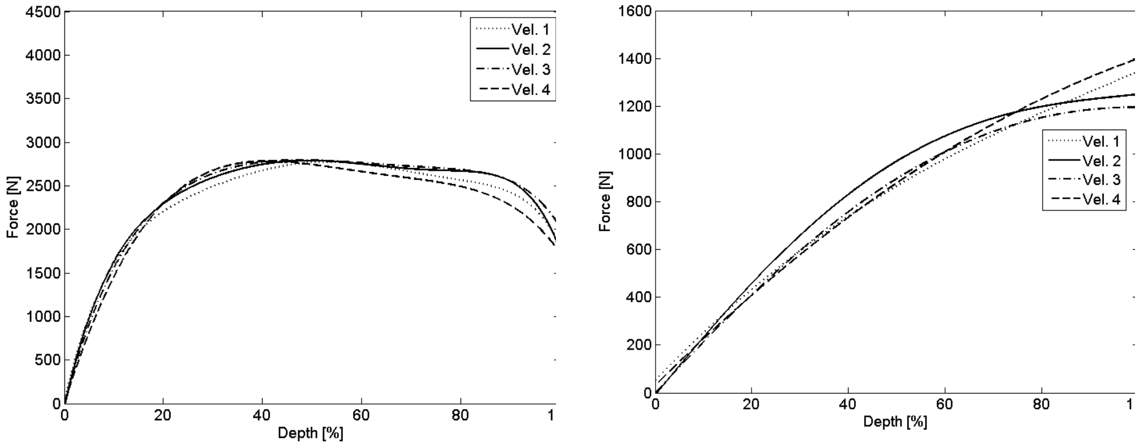

Figure 31: a) Vertical Force - DP 600 **b) Radial Force - DP 600**

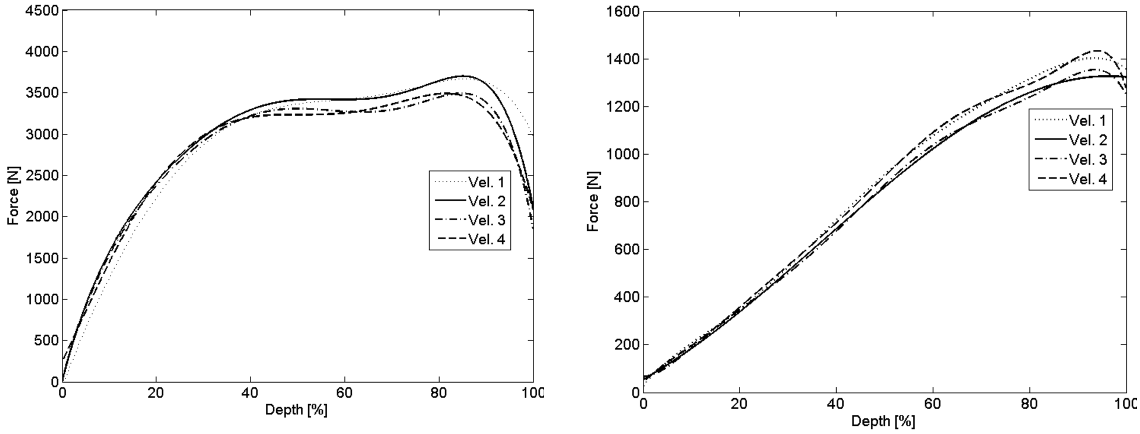

Figure 32: a) Vertical Force - DP 780 **b) Radial Force - DP 780**

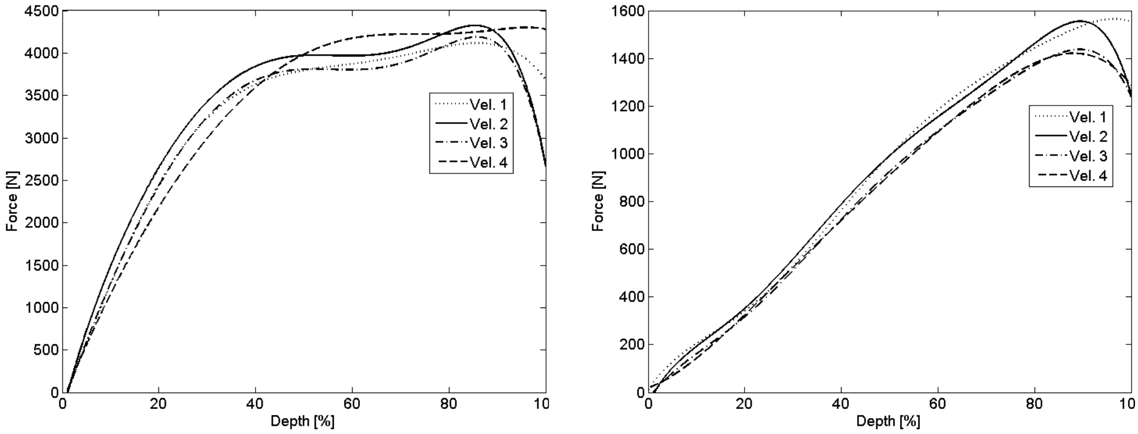

Figure 33: a) Vertical Force - DP1000 **b) Radial Force - DP 1000**

3.3.2 Formability

Incremental forming process is well known for its peculiar deformation mechanism and improved formability when compared to conventional press-forming operations. Doing so, traditional forming limit diagrams aren't much useful for incremental forming purposes. One of the most used measures to evaluate a given material formability under SPIF is the maximum wall angle (Duflou et al., 2008; Hussain et al. 2007).

Following this methodology, the formed frustrums were 3D measured (Figure 34) and maximum wall angle measured using a CAD software. Several measurements were taken to ensure repeatability and the presented values represent the mean value with a 95% confidence interval.

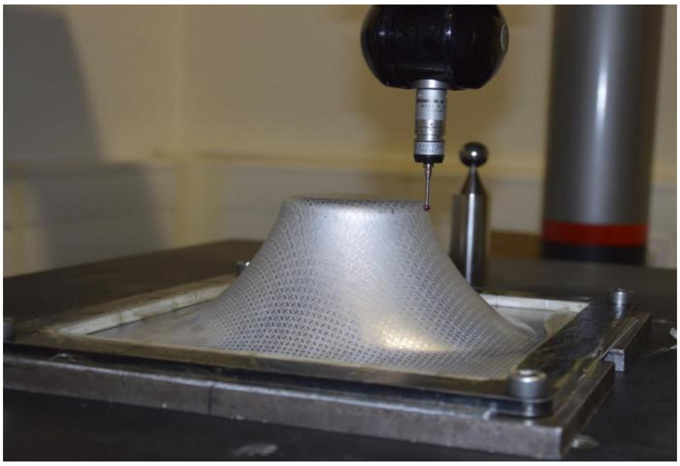

Figure 34: 3D profile measurement.

Results are summarized in figure 35. Oppositely to forming forces, results now give a clear idea of the effects deriving from feed rate

Aluminium alloy shows insensitivity regarding the feed rate, which is in agreement with the conclusions from Ambrogio et al. (2013). The case of DP600 steel, on the other hand, denotes clearly a decrease in formability properties with a reduction of 87° to 67°. DP780 and DP1000 show even less formability as having a wall angle starting from 67° and 63.5° degrees respectively and decreasing to 44° and 38°, but not linearly. In fact, after several repetitions, the maximum wall angle was kept for the feed rate of 1500mm/min for all DP materials, with minimum wall angles occurring for DP 780 e DP 1000. Summing up, DP600 material was the one showing greatest sensitivity to this forming parameter.

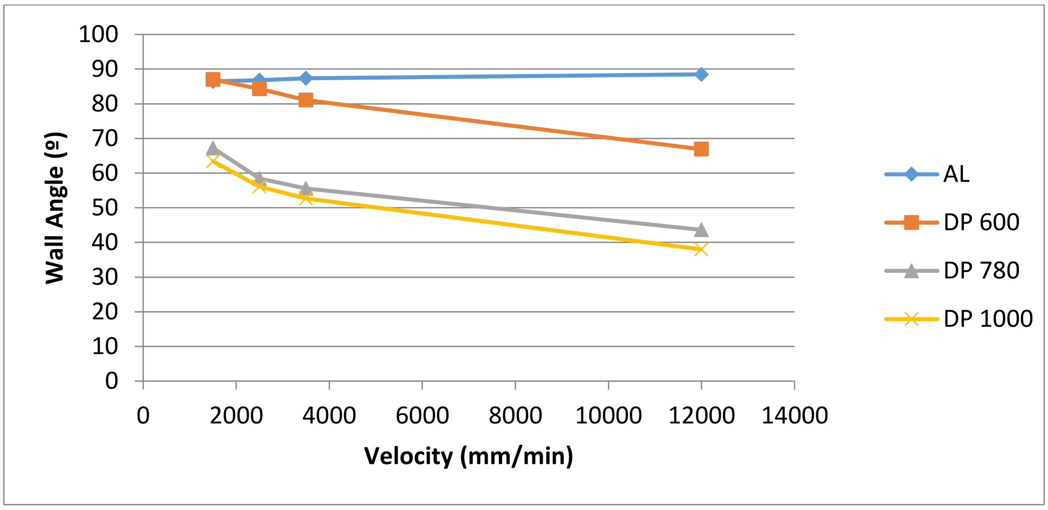

Figure 35: Wall angle regarding the rupture point vs Forming velocity

3.3.3 Fracture Forming Limit Curves (FFL)

The beneficial effect of incremental forming on increasing material formability is well-known and well- studied by many authors, especially concerning aluminium alloys. Typical forming limit curves (FLC) are represented in Figure 36. A better designation to these lines are Fracture Forming Lines. In fact, FLC's are determined mostly by necking, while in SPIF operations the continuous pressure from the tool during forming prevents and delay this phenomenon. Furthermore, due to the diffuse necking present in incrementally formed parts, the fracture forming line (FFL) seems more appropriate to characterize formability during incremental forming and typical curves are straight lines with negative slope. In this sense, FFL's were plotted for each material and for each feed rate studied, figures. 37 to 39.

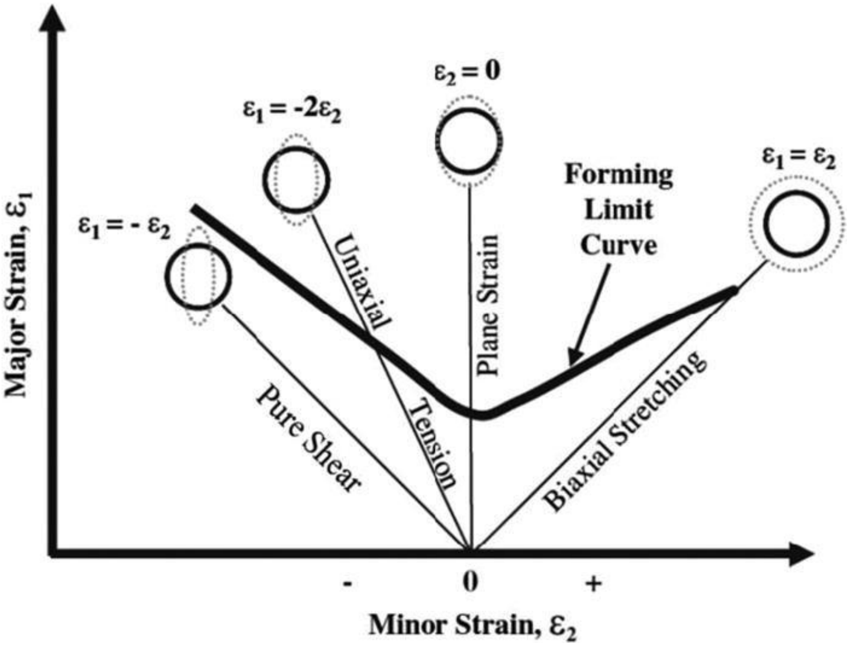

Figure 36 - Representation of FLC curve

The scale in both axis were kept unaltered to provide a more easy comparison between the different graphics. For AA1050-H111 (Figure 37) there is a high scattered set of points. Furthermore, it can be concluded that the effect of feed rate for this material is not significant. Finally, the magnitude of strain observed is in accordance with values observed by Camara (2009).

Focusing in dual-phase steels, there is no data available in literature for comparison. The softer DP600 (Figure 38) shows more formability than the harder DP780 and DP1000 (Figures 39 and 40). This is a straightforward conclusion. On the other hand, there is an evident sensitivity of the 3 grades concerning the feed rate. For DP1000, the decrease of formability is drastic, with limiting strains being reduced up to 3 times its initial magnitude. It becomes evident that feed rate must be carefully set when forming these types of steel to keep a good compromise between forming time and preventing necking and ultimately cracking.

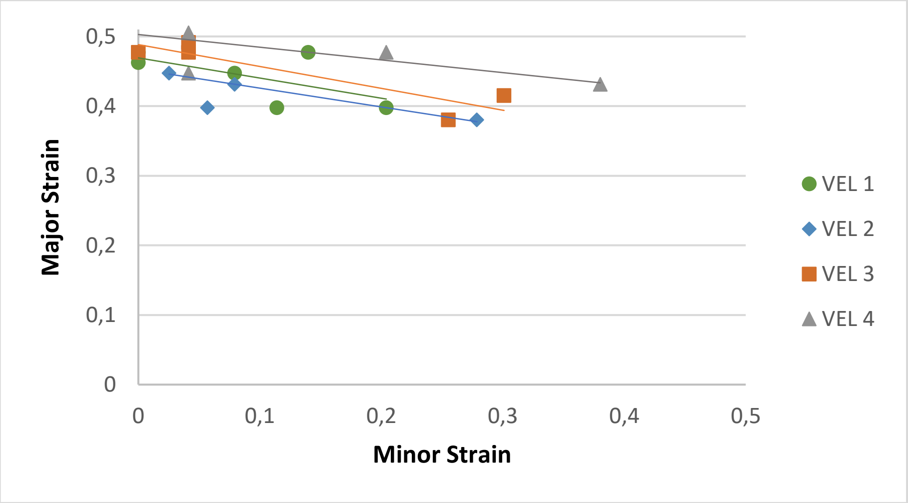

Figure 37 - FFL Aluminium

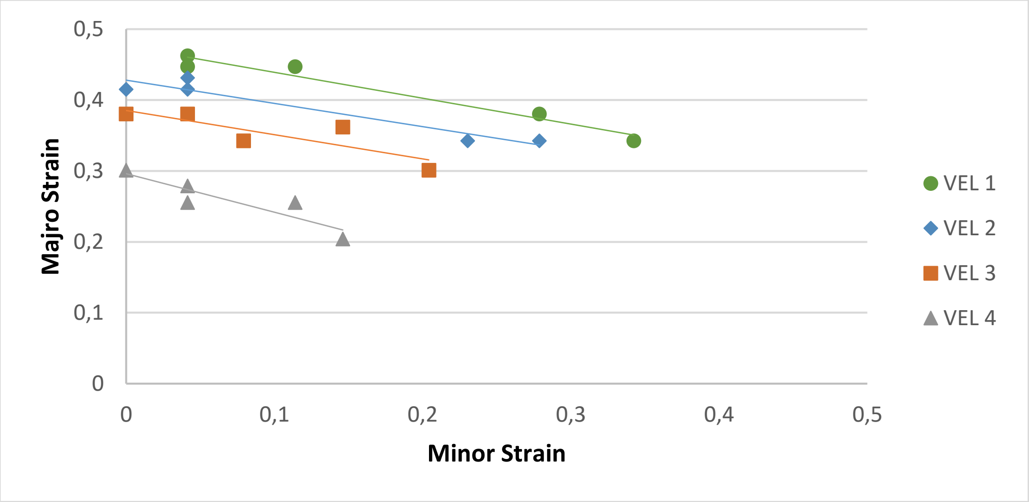

Figure 38 - FFL - DP 600

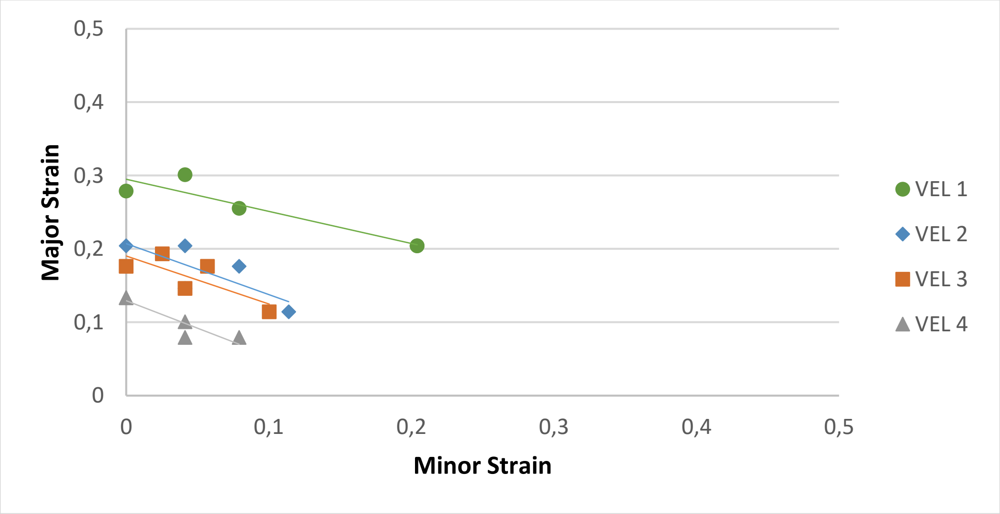

Figure 39 - FFL - DP 780

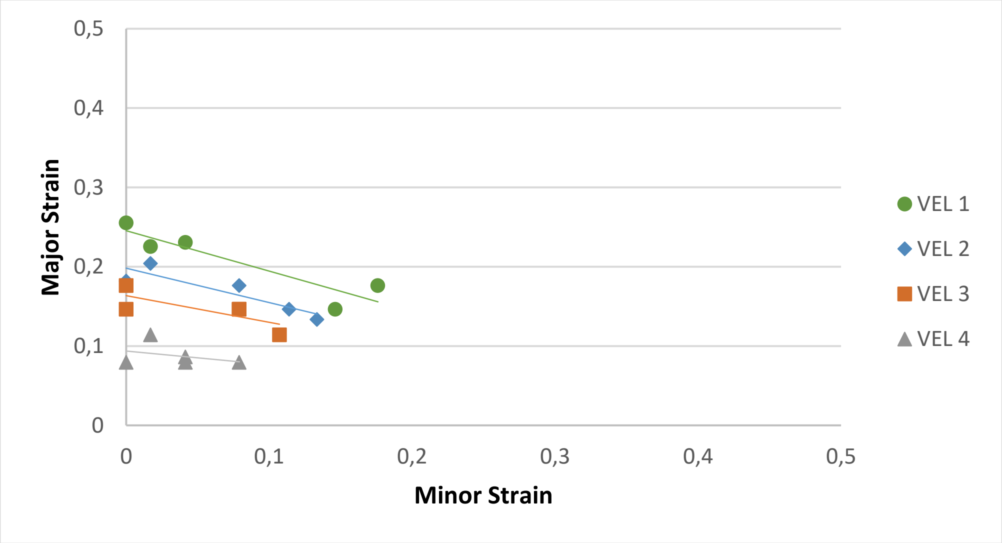

Figure 40 - FFL - DP 1000

3.4 Conclusions

Summing up, high production times are one of the factors impairing widespread use of incremental forming technologies for industrial applications, by limiting batch sizes for a fixed timespan. In this work, the effects of increasing the feed rate were studied in terms of forming forces, formability and surface finish. To minimize the number of experiments, tool diameter, lubricants and tool-path strategy were kept constant. However, the reader should keep in mind that a larger step down can also reduce forming times. Such effect has been studied for instance by Li et al. (2014).

Two types of material were assessed: one grade of aluminium AA1050-H111 and three grades of Dual-phase steel: DP600, DP780 and DP1000. Few results for these latter materials are present in literature given machine limitations, usually adapted milling machines, which is not the case of the SPIFA machine.

Results coming from forming forces, maximum wall angle of a frustrum geometry, fracture forming lines and roughness were clear and in agreement: increasing feed-rate reduces formability and deteriorates surface finish for dual-phase steels. Aluminium 1050-H111 appears to be insensitive to feed rate variations.

Resuming, it is naturally feasible to reduce forming times of simple parts, using a dedicated SPIF machine. For simple geometries, parts can be produced in a matter of minutes, allowing the production of medium sized batches in an acceptable timespan. However, reducing forming times for steel material will bring some pay-off which in this case would be less formability and worst surface finish that are visually checked. It will be up to the manufacturer to choose an acceptable feed rate to provide reliable and well finished parts to the final consumer, knowing that will be a commitment between production time, complexity of the geometry and the final quality of the product.

Chapter 4: Wrapping up and conclusions

Incremental forming technology was patented a long time ago in 1967, with initial real tests being performed in the nineties. However, proper industrial dissemination is still a long way to be a reality. Incremental forming has many characteristics that can guarantee a future in the industrial world. The high capacity of forming materials and the capacity to produce prototypes very quickly and cheaply is a very important asset for the manufacturers.

This dissertation work comprised a set of experiments that aimed to give a better insight into two important parameters in incremental forming technology: the lubrication and the process velocity (the feed rate). With this work is now possible to know that the lubricant is important for all the forming process giving a better surface quality to the products and minimizing the resultant forces. Another clear input to the bibliography is that using different lubricants will produce different quality of final surfaces, being the lower viscosity lubricants more appropriated for harder materials.

Regarding the influence of feed-rate, in theory the increase of feed-rate will produce worst results in surface finish and reducing the formability of the materials. The conclusions points that this theory can be applied to the steel but when the material is aluminium this correlation cannot be established. About the feed rate it will be a very crucial parameter for this technology because the production speed will depend on it and it will be a characteristic of the process that the manufacturers will need to optimize for each product depending of the final necessary requirements. In the future, with more knowledge about the optimization of all these parameters, it is expected that the production time do not be a negative point.

Additionally, it was possible, by using the in-house SPIF-A machine with large payload, to test high strength materials, like the class of dual-phase steels DP600,780 and 1000. The results presented show in that purpose-built machines definitively allow to ISF the possibility to expand the range of employed materials, and consequently the process possibilities.

Summing up, it is expected that this thesis can contribute for a better dissemination of incremental forming into industrial environment as a tool to produce customized products or small batches. Furthermore, it is intended to motivate other players (universities, manufacturers, and more) to invest in the development of the SPIF process, exploring their advantages to the conventional processes named in this thesis.

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