UNIVERSITAT POLITÈCNICA DE CATALUNYA
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Escola Politècnica Superior d'Enginyeria de Manresa

CONTROL ARM AND DESIGN OF ITS MANUFACTURING PROCESS

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MECHANICAL ENGINEERING DEGREE

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Abstract

This project consists in 4 sections. On the first section, the theory behind the main cold forming operations with sheet metal is explained, this is essential to understand some problems that may arise during those operations and take the necessary measures to avoid them. Furthermore, some basic theory about control arms, its types, materials and functions is given.

The second section consists on obtaining the 3D geometry by scanning a real control arm and creating the tools' 3D models which will be used on the third section of the project, the simulation.

This third section is the core of the project, where simulations are submitted and after the analysis of their respective results, some changes to the tools' geometry are made to obtain the final 3D models which are ready for production.

The tools' geometry is slightly changed through the several simulations performed in order to improve it, all without changing the end piece's dimensions considerably, since the target is to be able to manufacture that specific control arm.

Finally, with all the theory and the results obtained from the simulations, a possible automated process for manufacturing the control arm is given. That is only one possibility, since there are many options with slight differences, each one with its advantages and disadvantages. After analysing each one, the chosen one gives the higher automation, reducing the labour cost and time required for production, while incrementing the repeatability of the process.

After the completion of the last simulation, the deformation caused by the stamping process does not produce the failure of the piece, which means that the tools' final geometry is suitable and can be used in the real life process. On the contrary, the first geometry of the tools would have produced the breakage of the piece in all likelihood, as the results show.

Resumen

Este proyecto está dividido en 4 partes. En la primera, se explica la teoría detrás de las principales operaciones de conformado de chapa en frío. Este apartado es esencial para entender los posibles problemas que pueden surgir durante estas operaciones, de manera que se puedan tomar las medidas necesarias para evitarlos. Además, se explican los tipos, materiales y diferentes funciones que tiene un brazo de suspensión de un coche.

En la siguiente sección, se obtiene el modelo 3D utilizado en este proyecto escaneando un brazo de suspensión real y se crean las herramientas de deformación (el punzón y la matriz) a partir de este modelo.

La tercera parte es el núcleo del proyecto y consiste en realizar diferentes simulaciones para, con el análisis de los resultados obtenidos, modificar y pulir la geometría de las herramientas para conseguir que estén listas para ser utilizadas en producción.

Esta geometría se cambia ligeramente después de cada simulación para mejorar el proceso, pero siempre manteniendo las dimensiones dentro de unos valores próximos a los de la pieza que se quiere fabricar, es decir, el brazo de suspensión escaneado.

Finalmente, con toda la teoría y los resultados obtenidos de las simulaciones, se proporciona un posible proceso de producción automatizado para la fabricación del brazo de suspensión. Este es solo una opción, ya que hay muchas posibilidades con pequeñas diferencias, cada una con sus ventajas y desventajas. Después de analizar diversas posibilidades se escoge el que da un mayor grado de automatización, y, por lo tanto, reduciendo el coste de mano de obra y el tiempo requerido para la producción de las piezas, además de incrementando la repetitividad del proceso.

Después de completar la última simulación, la deformación causada por el proceso de embutición no produce el fallo de la pieza, lo que significa que la geometría de las herramientas es apropiada y puede ser utilizada en el proceso de deformación plástica real. Al contrario que en las primeras simulaciones donde se producía la rotura de la pieza al excederse el límite de rotura.

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GLOSSARY

Acronyms

ALLAE: Artificial strain energy

ALLIE: Total strain energy

FLD: Forming Limit Diagram

Variables

D_{hole}: nominal dimension of the hole (mm)

D_{die}: dimension of the die in a punching operation (mm)

$D_{outline}$: dimension of the blank (mm)

D_{punch}: dimension of the punch in a punching operation (mm)

F_{bend}: force required to perform a bending operation (N)

F_{dr}: force required to perform a drawing operation (N)

F_s: shear force required for performing the punching or blanking operations (N)

K_{nf}: factor of position of the neutral fiber

K_r: elastic recovery factor

L_{nf}: neutral fiber length (mm)

P_s: power required to perform the punching or blanking operations (W)

R_d: bend radius (mm)

R_f: desired bend radius (mm)

R_i: bend radius before the elastic recovery (mm)

S_{blank}: area of the blank (mm^2)

S_s: area of the outline of the cut (mm^2)

S_{used}: area of sheet metal used to obtain a blank (mm^2)

k_1: factor that depends on the material for the first drawing step

k_2: factor that depends on the material

k_{fd}: factor that depends on the type of bend

l_0: initial length of the elongated element

α_f: desired bend angle (deg, rad)

α_i: bend angle before the elastic recovery (deg, rad)

σ_T: tensile strength (MPa)

σ_S: shear stress limit (MPa)

h: drawing's depth (mm)

D: main dimension of the blank before the drawing operation (mm)

$PEEQ$: plastic strain equivalent distribution

$S, Max\ Principal$: Maximum principal stress distribution (MPa)

$S, Mises$: Von Mises Stress distribution (MPa)

$SDEG$: damage variable in *Abaqus CAE*

STH: thickness variable in *Abaqus CAE* (mm)

U: displacement (mm)

a: ratio d/D in the drawing operation

c: clearance between the punch and the die in a punching operation (mm)

c': effective displacement of the punch (m)

d: main dimension after the drawing operation (mm)

e: elongation

k: safety factor

l: distance between supports (mm)

l: length of the elongated element

m: factor that depends on the drawing's depth

p: perimeter of the cut (mm)

r: material efficiency (%)

s: thickness of the sheet metal (mm)

t: time required to perform the punching or blanking operations (s)

w: width of the bend

α: bend angle (deg, rad)

1. INTRODUCTION

A control arm is an essential part of any car. The manufacturing process of this part has evolved by the years and now it is commonly produced by sheet metal stamping, since it has a reduced cost and allows to produce high quantities of it.

Even if all the cars turn electric in the future, as long as they stay on the road, it will continue to be necessary to manufacture this part. And this is what this project is about, describing, designing and simulating the stamping process of a control arm.

Due to that every manufacturer produces its own parts, there is a lot of confidentiality and it is very difficult to find 3D models of a control arm or even just a little description of the process to manufacture it. For this reason, it could be very useful to describe the process and analyse it.

1.1. OBJECTIVES

The main target of the project is to determine the design of the manufacturing process of a control arm, using CAD software to design the tools and finite elements methods software to simulate the operations carried out with those tools.

The steps to follow in order to achieve the main objective are gathering all the information needed to determine the operations of the process, designing the tools, simulating the process, and analysing the results of the simulation in order to make the necessary improvements.

Apart from the mentioned objective, there are others that are more personal, such as learning the theory behind the stamping process in detail and learning how to simulate it with a certain degree of precision.

That said, it is important to highlight that this project doesn't have as a target to describe how the CAD design of the control arm is obtained. Hence, there will be little information about this, in order to focus on the main point, which is the process of manufacturing by cold stamping.

1.2. MOTIVATION

Being true that the design of any part is essential for defining some requirements, such as tolerances or surface hardness, the part itself has to be manufactured in some way, and it is the process of manufacturing that defines whether those requirements are satisfied or not.

Having studied a subject about materials' forming, I've noticed how influential it is to choose the right way to manufacture a certain product, either on the quality of the end product or its cost.

Reducing the cost of manufacturing is one of the most valuable tasks of an engineer, since it increases the benefits for the company. That said, simulating the process of manufacturing a control arm should help reduce the cost of the part, since it ensures that it could be manufactured and saves vital time and raw material.

1.3. FRAME

The study will start by exposing the current manufacturing method of a control arm.

The following step would be to obtain a 3D model of a control arm as realistic as possible.

To continue, it is going to be necessary to determine the steps needed to manufacture the part, whether it could be produced in one single stage or it will take several operations to manufacture, each operation giving the metal sheet a more similar look to the end piece.

After this essential step, it is time to design the tools and set up the simulation for the process of manufacturing the control arm.

Finally, it is vital to analyse the results correctly and make the necessary improvements on the tools design or the process itself.

This two final steps should be repeated till the results show no damage to the end product.

Even though this analysis will be performed on a certain product, the methodology used to set up the simulation and analyse its results can be extrapolated to any other part manufactured by stamping.

1.4. PROJECT REQUIREMENTS

Like all the projects, this one has also some important requirements. In this case, the part itself is a control arm, which has to support important stress because it joins the chassis and the suspension. For this reason, it is important to highlight that the geometry of the part is going to be as similar as possible to a real control arm of a car which has been 3D scanned.

For the same reason, the thickness of the part should be enough to support all the stress, that is why the metal sheet which is going to be used for the simulations will have a thickness of 3mm, the same as the real one.

2. STAMPING PROCESS

Stamping (also named pressing) is the manufacturing process which transforms a flat sheet metal into the desired shape by pressing it between a tool and a die. In this process, the thickness of the sheet metal remains constant, in contrast with other techniques like forging.

2.1. HISTORY OF THE STAMPING PROCESS AND CURRENT APPLICATIONS

It has been a long time since the first stamping was performed. It is believed that the beginning of this process was around the seventh century B.C. in Turkey. They started to stamp an image on both sides of a coin using a hammer and a die, which had the negative shape of the image that was to be stamped on the metal surface. These coins were made using gold or an alloy of gold and silver.

Figure 1: First coins in the world. [28].

Eventually, the population saw the potential of this process and began to stamp other objects and with the coming of the industrial revolution the way of exerting the pressure onto the metal changed from human brute force to steam powered.

Over time, this process has been through continuous changes and now with the advancements in electronics it is even possible to control the speed at which deformation occurs. Furthermore, those improvements have led to high precision results.

There are many industries that nowadays take advantage of the metal stamping process. Some industries that employ this process include: automotive, machinery, electronics, electrical and aerospace.

2.2. SHEET METAL FORMING DEFINITION

Sheet metal forming operations include a variety of manufacturing processes which use plastic deformation to shape those sheets of metal. In general terms, a punch exerts a stress that exceeds the elastic limit, giving the sheet metal the shape of the punch permanently. Otherwise, if the elastic limit is not exceeded, the changes in shape produced will not be permanent, and therefore the sheet metal will return to its original shape when the punch releases it.

When plastic strain is produced below a certain temperature, the microstructure of the metal changes to a finer grain with higher density of dislocations, which produces a hardening of the metal by effect of the plastic strain.

So this type of metal forming operations is not only used to give a particular shape to a sheet, but also to improve its mechanical properties.

Some plastic deformation processes bend the sheet, others cut it with the desired outline or make holes, while others stretch it. Some of the most common processes used in today's industry are the following:

- Punching: the punch exerts a high amount of force to produce holes and cutouts on the sheet.
- Blanking: the sheet is trimmed to get a first shape for further processing.
- Embossing: the material is stretched into a shallow depression.
- Coining: a pattern is compressed into the material (traditionally used for coins, see *Section 2.1*).
- Bending: the sheet metal is bent along a straight line a specific angle.
- Flanging: the material is bent along a curved line a specific angle.
- Drawing: the blank is deformed or curved throughout the die's surface.
- Deep drawing: similar to drawing but the depth of deformation is considerably higher.
- Stretching: the surface area of a blank is increased by tension.
- Ironing: the material is squeezed and its vertical walls are reduced in thickness.
- Reducing/Necking: used to reduce the diameter of the open end of a tube.
- Curling: deforming material into a tubular profile (ex: door hinges).
- Hemming: folding an edge over onto itself to add thickness (ex: automobile doors).

Some simple shapes can be obtained by just one of those techniques, while obtaining a complex shape usually requires of the combination of some of those operations, as in our case.

In the figure below, it is easy to appreciate the different forming operations that have been used to manufacture the control arm that that will be studied in this project.

Figure 2: Operations performed to obtain a control arm.

The first operation performed is the blanking and the punching, then the rest of operations could have been performed all at once, with a unique movement of the punch, or they could have been performed one by one, with progressive die stamping (explained in *Section 2.3*).

In general terms, the operations can be grouped in 3 types: cutting, bending and drawing (see *Section 2.4* for a detailed explanation of those).

2.3. TYPES OF METAL STAMPING

In broad terms, there are three types of metal stamping: progressive, four-slide and drawing/deep drawing, each one of them has its advantages and disadvantages, so it is an important task to decide which process to use to manufacture a certain part.

2.3.1. PROGRESSIVE DIE STAMPING

Progressive dies feature a number of stations where a unique function in each station is conducted. Though only one function is performed in each station, all the stations perform their respective operations at the same time.

When the strip of metal coming from a coil unrolls and enters the die press, it gets from one station to the following one successively until the final product comes out from the final stage.

This type of process reduces the labour cost and has a higher repeatability, which makes it ideal for complex parts where many operations should be performed to obtain the end product. Also, it is really efficient for large series, since it is highly automatable.

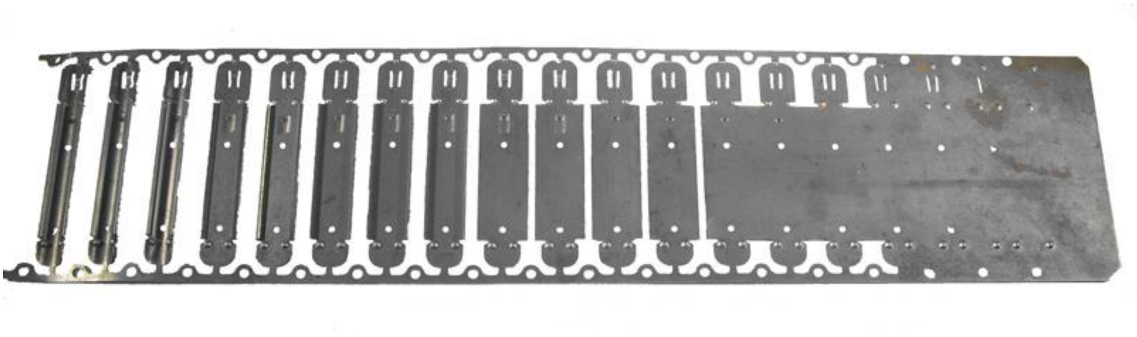

Figure 3: Piece manufactured by the progressive die stamping process. [15].

Figure 3 shows a piece of metal strip that was taken out of the die in the middle of the process which makes it easy to understand which operations were performed at which stage or station in the die.

For large series of production, it is very common to use a sheet metal roll, which is pushed toward the press to perform the required operations. In this type of metal stamping, positioning the sheet at the right position every time the punch descends is essential, hence the importance of having an automatic feeding machine.

2.3.2. FOUR SLIDE STAMPING

This type of stamping process uses a horizontal stamping press equipped with four shafts to control the tools attached to slides. Instead of the usual vertical motion, the four slide machine works on right angles and since it has slides on the four sides it is extremely versatile. When the material feeds into a four slide machine, it is bent quickly by each of the four shafts that is equipped with a tool. Because of its construction, there are some operations that cannot be performed with this kind of press, but it is ideal for other operations such as bending.

2.3.3. DRAW STAMPING

Drawing involves pulling a sheet metal blank into the die via a punch, forming it into a shape. The die and the punch should have the reverse shape of the piece. The term deep is used when the depth of the drawn part exceeds the diameter of the piece.

When deep drawing is performed, the reduction of the sheet metal's thickness should be taken into consideration, since there could be areas where the thickness of the walls gets dangerously thin of ever breaks.

2.4. SHEET METAL FORMING OPERATIONS

To start with, there are some variables that should be controlled in order to affect others. Those are the independent variables of the process, which are the following:

- Material and its properties
- Blank shape before the process
- Shape of the tools
- Lubrication
- Initial temperature
- Amount of deformation

Controlling these variables is essential to obtain the desired dependant variables, which are:

- Energy consumption
- Product properties
- Product geometry
- Surface finish
- Final temperature
- Dimensional precision

If the objective is to reduce the energy consumption and improve the surface finish, it is essential to have a good lubrication system to reduce the energy waste because of the friction. If the geometry of the end product does not meet the dimensional tolerances, it is essential to define correctly the outline of the blank before the process. Or if the product is really deep and there is need of high levels of deformation to manufacture a certain part, maybe the material used should be at a certain initial temperature.

Therefore, sheet metal forming processes are a true science, and many factors should be taken into consideration when these operations are performed. In this section, there will be an overview of the factors that affect the deformation processes.

2.4.1. GENERAL FACTORS

One of the most important factors that should be taken into consideration is the raw material of the sheet metal itself. It should have a high degree of formability and a low elastic limit, in other words, it has to be able to deform with ease.

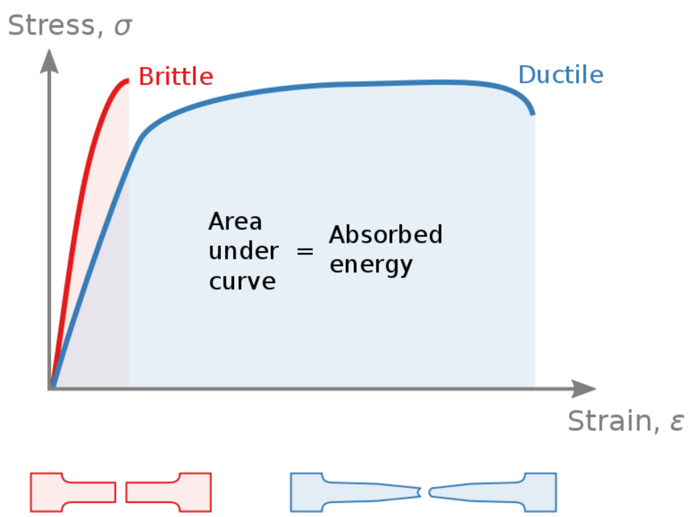

Figure 4: Stress - elongation curve difference between brittle and ductile metal. [36].

The most frequent materials used in industry are carbon steel, stainless steel, aluminium, high strength steels (very common in the automotive industry), and other materials such as titanium, magnesium or cooper.

One way to understand if a material can be deformed up to a certain point is using the Forming Limit Diagram.

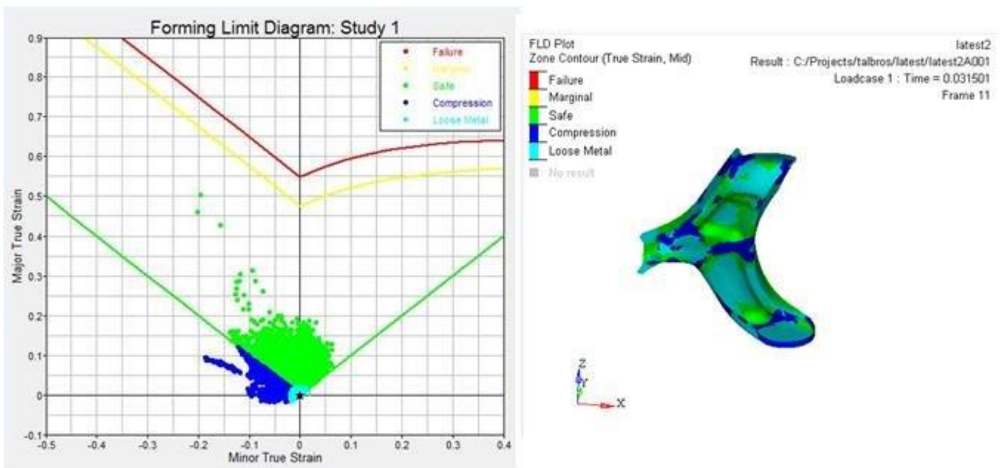

Figure 5: Forming Limit Diagram Curve. [13].

These curves are created by experimentation. A proof is tested in many tension states until it breaks, creating the failure curve. Every tension state falling between the red and green curves is in the safe zone, so the piece won't break. This is really useful when the deformations needed to manufacture a certain product are known.

An FLD curve will be used in *Section 7.4* in a simulation, so that if the piece breaks, the results will show the failure.

2.4.2. SHEET METAL PUNCHING

Punching is used to make holes in the sheet metal either with circular shape or with any other shape.

The process has several phases as *Figure 6* shows:

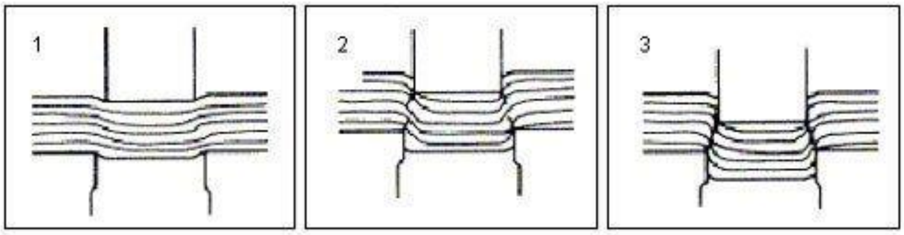

Figure 6: Phases of the punching operation. [23].

1) The punch descends upon the sheet metal causing first an elastic deformation and then a plastic one.
2) The punch continues to descend penetrating into the sheet.
3) Fracture occurs, separating the material below the punch from the sheet metal.
4) Expulsion of the scrap material.

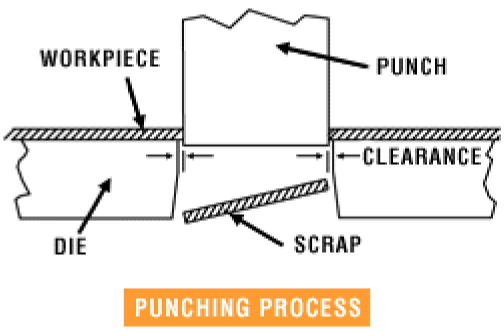

Figure 7: Sheet metal punching diagram. [4].

Figure 7 shows how a hole in a sheet metal is conducted. There are several important aspects that should be taken into consideration in this case to get a good result without burrs and the minimum amount of scrap material possible.

The surface finish of the hole is often of great importance and it can cause non-conformities because of the possible burrs.

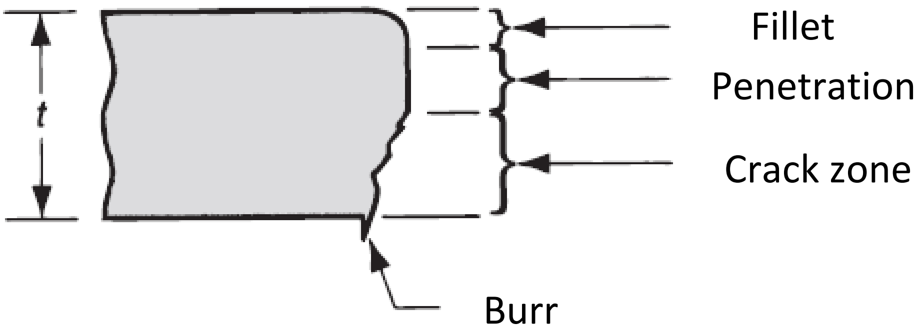

Figure 8: Surface finish of a punched hole. [24].

Figure 8 shows the surface finish after making a hole by punching. The punch started deforming the sheet metal at the superior part (1), it is easy to appreciate that because of the radius produced in that zone. Then, the middle part (2) shows the zone where the phase of penetration occurred. Then, when the stress exceeded the fracture limit, a fracture was produced in the inferior part (3). Finally, there is a burr at the lowest point (4) due to the separation of the scrap from the sheet.

In many cases, the burr can be removed with a posterior operation, but in some cases that is impossible, so it is of great importance to try to reduce the burrs or eliminate them.

The main causes of burrs are:

- An excessive or insufficient clearance between the punch and the die.
- The wear of the punch or the die
- A bad alignment of the punch respect to the die through any point of the operation
- A deficient maintenance
- Buckling of the punch

Therefore, it is important to have a good maintenance of the tools, design them correctly and adjust the clearance with high precision.

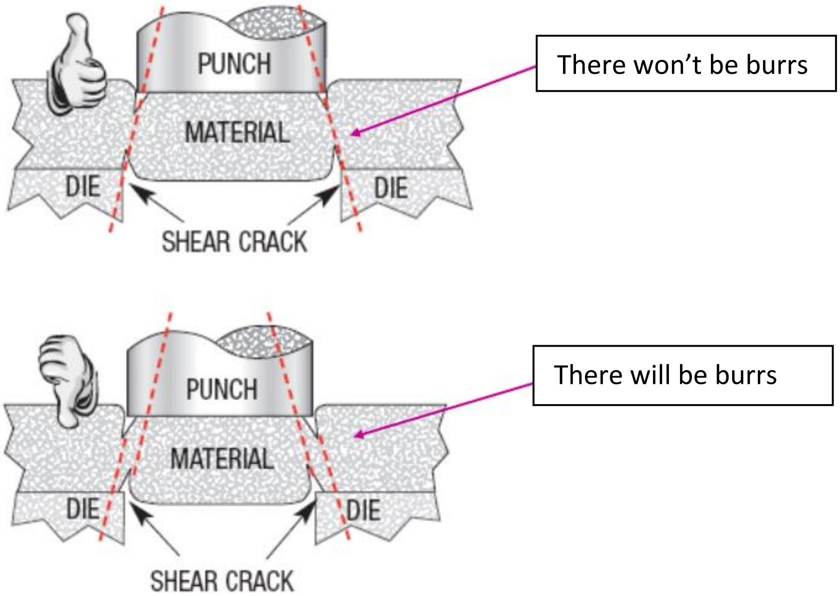

Figure 9: Clearance effects on the surface finish. [5].

Adjusting the clearance is crucial since if the crack produced by the die coincides with the one produces by the punch, there won't be any burrs. The clearance depends on the tensile strength of the sheet metal and its thickness, usually its value is between 2 and 10% of the thickness of the sheet metal.

The clearance should be obtained increasing the dimensions of the die, and the dimensions of the punch should remain the same as the hole.

$$D_{die} = D_{hole} + c$$

$$D_{punch} = D_{hole}$$

In addition, a holder should be used to fix the sheet so it does not move during the operation (see *Figure 10*). It is also useful to avert the sheet from gripping to the punch and avoid possible distortions.

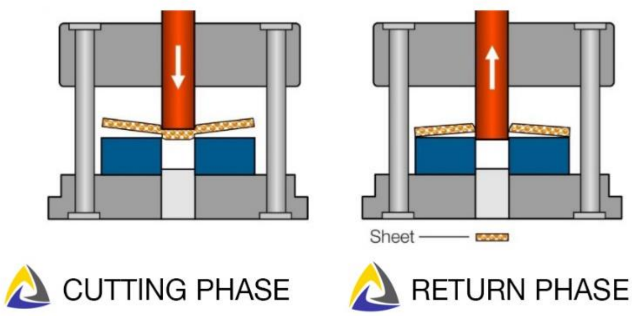

Figure 10: Punching without holder effects. [3].

Finally, to ease the expulsion of the scrap, the die is given a discharge angle of -1º making it slightly conical.

2.4.3. SHEET METAL BLANKING

The same principles can be applied to metal blanking with a few differences.

The first one is that the clearance in this case should be applied to the punch, reducing its dimensions, while the die should remain with the same dimensions as the blank.

$$D_{punch} = D_{outline} - c \qquad \text{Equation 1}$$

$$D_{die} = D_{outline} \qquad \text{Equation 2}$$

The other difference is that in this case, the amount of scrap material should be reduced to the minimum since metal has a cost and it should be taken into consideration.

The amount of scrap is highly dependent on how the blanks are disposed.

- Normal disposal

In this disposal, the pieces are placed one next to each other letting a separation between them, this kind of disposal is really efficient for rectangular pieces or pieces that can be inscribed in a rectangle.

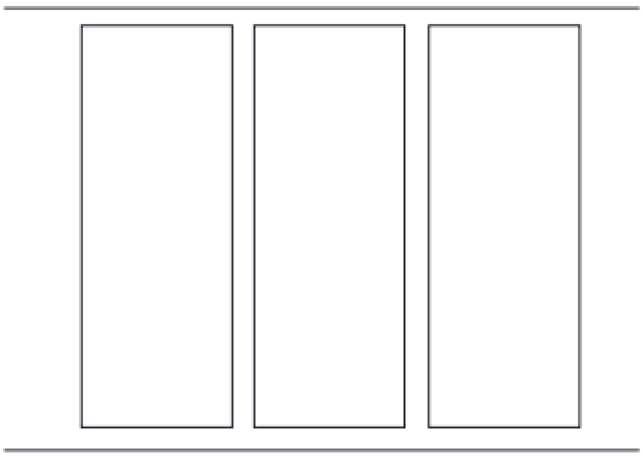

Figure 11: Normal disposal. [17].

- Oblique disposal

In this kind of disposal, the pieces are placed one next to each other at a certain angle. This is really useful for pieces that can be inscribed in a triangle.

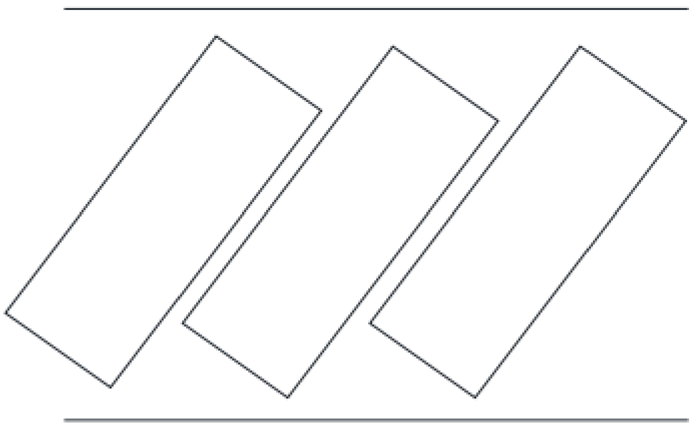

Figure 12: Oblique disposal. [17].

- Inverted disposal

The position of the pieces on the sheet is alternatively rotated 180º. This disposal is convenient for pieces with an extreme wider that the other extreme. For this disposal, 2 punches are needed, the normal and the inverted.

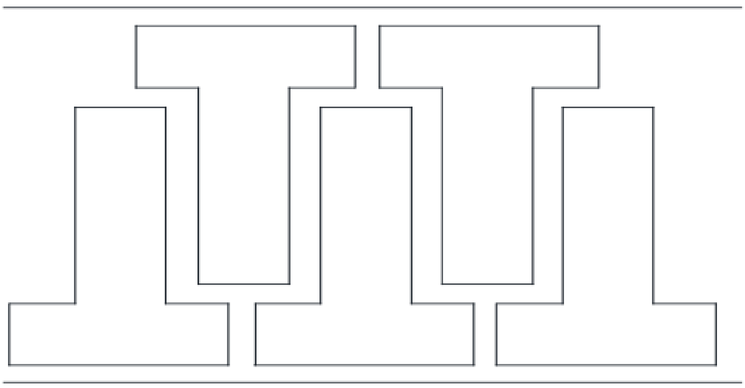

Figure 13: Inverted disposal. [17].

- Multiple disposal

In some cases, when large series are produced, the pieces can be placed so that the punch can cut several pieces at once. Because of the cost of multiplying the number of punches, this disposal is never used for short series.

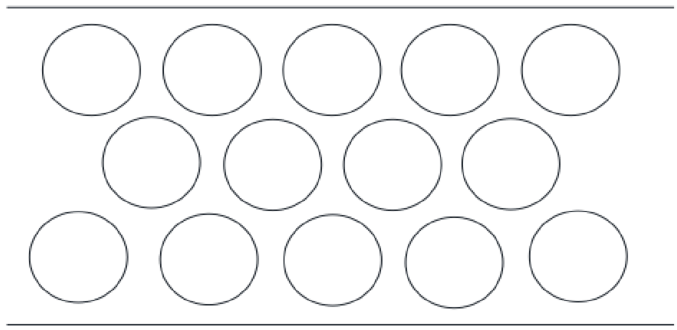

Figure 14: Multiple disposal. [17].

To compare the different disposals, the term material efficiency is used:

$$r = \frac{S_{blank}}{S_{used}} \cdot 100\% \qquad \text{Equation 3}$$

Where S_{blank} is the area of the blank and S_{used} is the area of sheet metal used which can be calculated as a product of the width of the sheet and the pitch.

The pitch is the distance between one point in one piece and the same point in the next piece. It does not only depend on the geometry of the blank, but also on the separation between them.

This separation is stablished as two times the thickness of the sheet if the intersection is linear or one thickness if the intersection is punctual (only one possible point of contact).

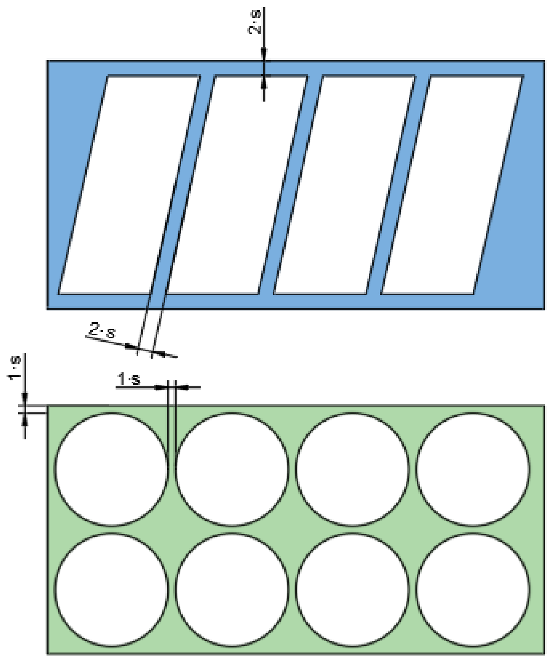

Figure 15: Separation piece-piece and piece-sheet.

As an example, in *Figure 15*, the pitch for the disks can be calculated as the diameter plus the thickness, and the width can be calculated as 2 times the diameter (d) plus 3 times the thickness (s). Therefore, the material efficiency in that case is:

$$r = \left(\frac{\pi \cdot \frac{d^2}{4}}{(d+s) \cdot (2 \cdot d + 3 \cdot s)} \right) \cdot 100\%$$

Before any production process this value should be calculated in order to get the lowest amount of scrap material possible. Otherwise, there may be economical losses due to the need of higher quantities of raw material.

2.4.4. SHEET METAL BENDING

The bending operation consists on applying a force on a sheet metal so it bends a certain angle with regards to a straight axis. This forming operation should not change the thickness of the sheet at any point, and the sheet area should remain constant.

The most common types of bending are these ones:

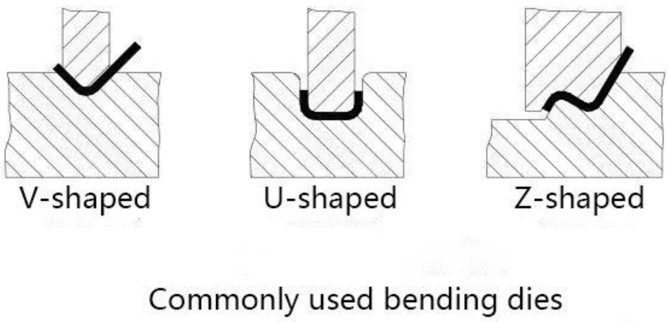

Figure 16: Types of bending operations. [19].

When performing a bending operation, some factors should be considered:

- The positioning of the sheet (there should be no movement when the operation starts).
- Exerting the proper force to bend the sheet.
- Selecting the right bending radius.
- Good contact between the surfaces of the punch and the sheet (both sides should be clean).

The aspects that define the final shape are the bending angle, the inner bending radius and the elasticity of the material. However, it is really important to know the rolling direction, since it has a huge effect on the material's tensile strength and other mechanical properties. Because of the grain orientation and shape after rolling, to obtain the maximum tensile strength, the bending axis should be perpendicular to the rolling direction. Otherwise, if the bending angle is too high, cracks may appear or even the piece could break.

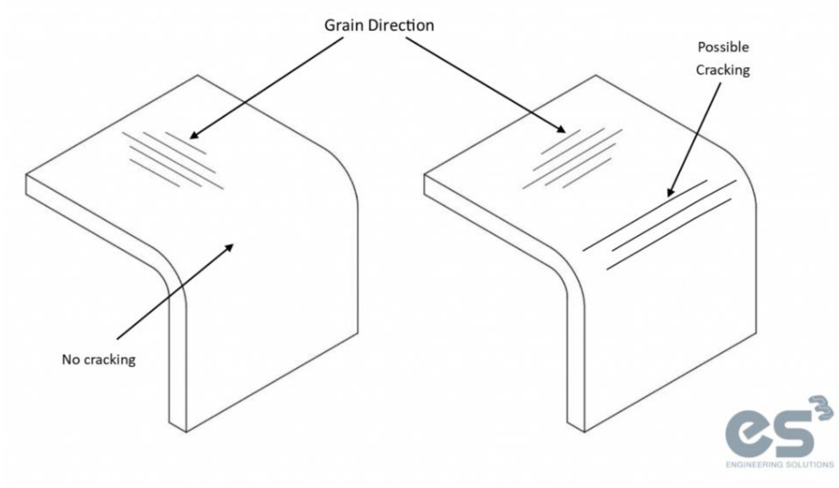

Figure 17: Bending orientation regarding the rolling direction. [10].

Placing the bending axis at 45º regarding the grain orientation could also help to reduce the negative effect of this.

Before proceeding to the calculus, it is important to overview the foundations of bending.

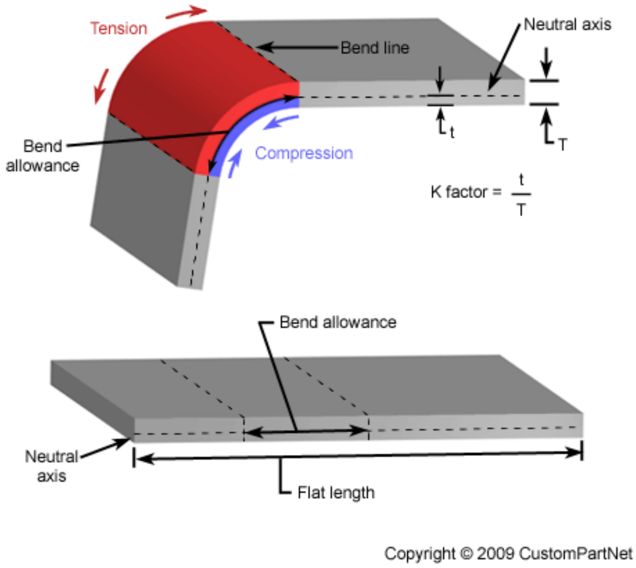

Figure 18: Tensions and variables of the bending operation. [9].

The neutral axis is the line which separates the tension and compression zones, as shown in *Figure 18*. In this case, the upper side of the sheet is at tension and beneath the neutral axis there is compression, that in because the outer side has a higher radius than the inner side.

In the neutral axis the tension is null and its length should remain the same through the process. Its position is not in the middle of the sheet, but it changes depending on the thickness and the bending radius.

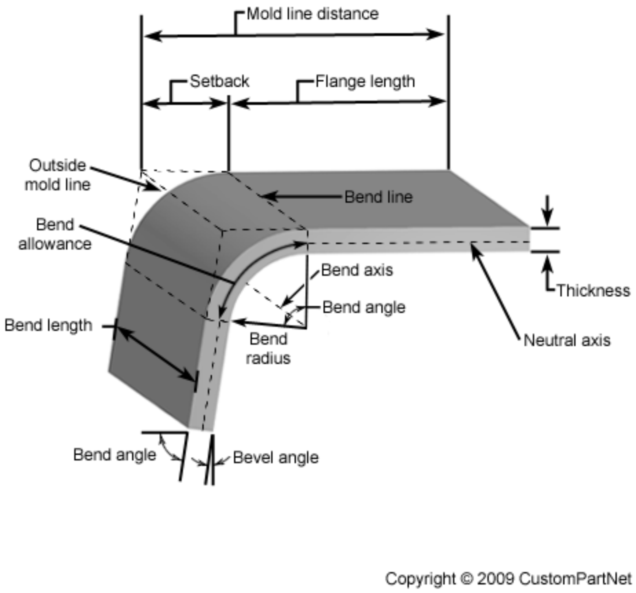

Figure 19: Bending operation variables. [9].

When the sheet is bent a certain angle (α), an inner bending radius (R_b) appears. This radius should be greater than the thickness of the sheet to avoid stretching too much the outer layers and causing its breakage, for this reason, the minimum inner bending radius Rd is defined.

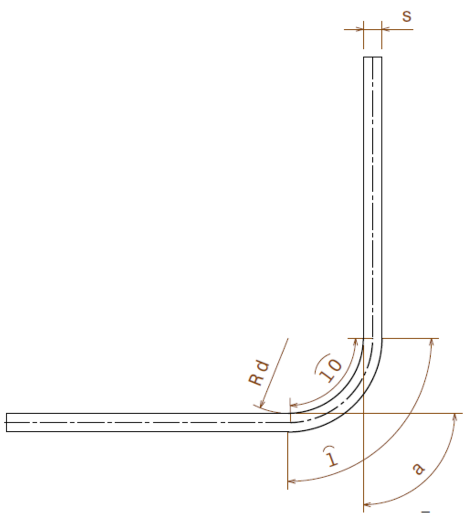

Figure 20: Variables involved in the calculation of the minimum bending radius.

The elongation is defined as:

$$e = \frac{l - l_0}{l_0} \quad \text{Equation 4}$$

If this equation is developed further:

$$e = \frac{l - l_0}{l_0} = \frac{\alpha \cdot (R_d + s) - \alpha \cdot (R_d + s/2)}{\alpha \cdot (R_d + s/2)} = \frac{s/2}{R_d + s/2} = \frac{1}{R_d \cdot \frac{2}{s} + 1}$$

Isolating the ratio between the minimum radius and the thickness from the equation:

$$e = \frac{1}{R_d \cdot \frac{2}{s} + 1} \rightarrow \frac{R_d}{s} = \frac{1}{2} \cdot (\frac{1}{e} - 1)$$

$$\frac{R_d}{s} = \frac{1}{2} \cdot (\frac{1}{e} - 1)$$ Equation 5

This way, if the thickness of the sheet and the maximum elongation of the material are known variables, the minimum radius with which the sheet metal can be bent can be calculated with *Equation 5*.

Another essential aspect of the bending is the elastic recovery or 'springback', when the punch stops exerting pressure onto the sheet. It consists on a reduction of the bend angle and an increase on the bend radius. This elastic recovery should be calculated and compensated, which is not an easy task and if not done properly, the dimensions could not meet the final product requirements.

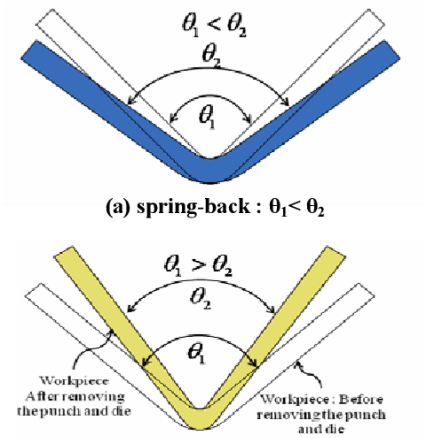

Figure 21: Elastic recovery after removing the punch from the sheet metal. [37].

This elastic recovery increases the higher the tensile strength is, it also increases the higher the bend radius is and the lower the thickness is.

To quantify this elastic recovery in order to be able to compensate it with precision, the subscript 'i' is defined for the desired value of a variable (before elastic recovery) and the subscript 'f' for the real value of a variable (after the elastic recovery). The elastic recovery factor (K_r) is defined as well with the following expression:

$$K_r = \frac{\alpha_f}{\alpha_i}$$ Equation 6

Knowing that the length of the neutral axis should remain constant, the following equation can be written:

$$\alpha_i \cdot \left(R_i + \frac{s}{2}\right) = \alpha_f \cdot \left(R_f + \frac{s}{2}\right)$$ Equation 7

If the elastic recovery factor is a known value (from experimentation), the equation below expresses the initial bend radius in order to obtain a certain bend radius after the spring-back takes place.

$$R_i = K_r \cdot \left(R_f + \frac{s}{2}\right) - \frac{s}{2} \qquad \text{Equation 8}$$

Now, knowing the values for the bend angle and radius before elastic recovery, we can adjust the tools with this values to obtain the desired ones.

Finally, the calculus of the sheet dimensions before bending could save time and money by avoiding the production of prototypes to test.

The data we need to perform this calculation is the thickness, the dimensions of the final product and the position of the neutral fiber.

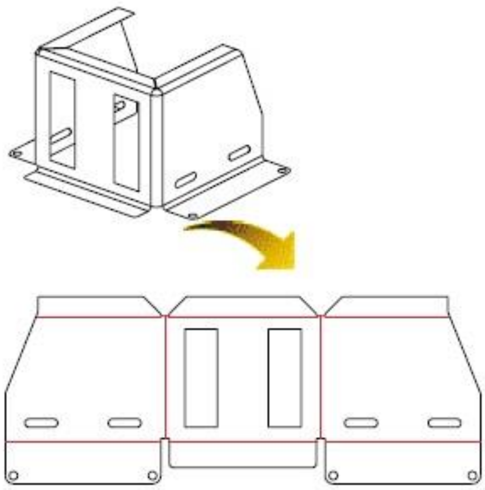

Figure 22: Sheet metal development. [2].

The length of the neutral fiber does not change when bending, so that is length that should be used to calculate the development of the sheet. The length of the neutral fiber (L_{nf}) in a curve can be calculated as:

$$L_{nf} = \alpha \cdot (R_d + K_{nf} \cdot s) \qquad \text{Equation 9}$$

Where K_{nf} depends on the position on the neutral fiber and its value goes from 0,33 if the bend radius is two times lower than the thickness to 0,5 if it's higher.

2.4.5. SHEET METAL DRAWING AND DEEP DRAWING

Drawing is the process in which a punch exerts a force on a sheet metal giving it the shape that remains between the die and the punch itself.

This process is one of the most used to manufacture metal containers and other sheet metal parts, like the control arm that will be analysed in this project.

This operation is the most complex one, since large deformations are produced with complex tensional states. It also requires large forces, which can produce wear and deformation on the tools.

Figure 23: Stepped deep drawing. [33].

Types of drawing

This operation can be classified as simple drawing or deep drawing depending on the ratio between the initial diameter of the piece and the final diameter:

- Simple drawing

  When the following relation is satisfied.

  $$\frac{d}{D} < 0{,}56$$

  Where d is the diameter after drawing and D is the initial diameter of the disk.

- Deep drawing

  When the following relation is satisfied.

  $$\frac{d}{D} < 0{,}56$$

  Where d is the diameter after drawing and D is the initial diameter of the disk.
  In this case, the drawing should be done in different steps to avoid problems in the final piece.

Holder characteristics

First of all, in this case the holder should allow the sheet metal to slide, so the pressure it needs to exert should be calculated considering this factor. If the force is too high, the sheet won't slide enough and it may break because of an excessive stretching. If it is too low, wrinkles may appear causing and the piece might not serve its purpose.

Figure 24: Wrinkles due to the holder pressure. [25].

For more complex parts, the use of a flexible holder is needed. This allows having several points where pressure is applied with a certain value.

Tools' roundness

To continue, the tools should have a rounded shape, in other words, since this operation's target is not cutting, there should not be any sharp edge and the areas of the tools that are in contact with the sheet should be polished to reduce friction.

With high radius, the holder might not have the desired effect, thus the process may result in wrinkles. With low values of radius or sharp edges the sheet would grip to the edges of the punch producing its fracture.

The ideal roundness can be calculated with the following formula:

$$R = 0{,}8 \cdot \sqrt{(D-d) \cdot s}$$ Equation 10

Where D is the initial diameter of the disk, d is the final diameter of the piece and e is the thickness of the sheet.

The usual values are the following ones:

If s < 1mm → R = 6·s a 8·s

If 1mm < s < 3mm → R = 4·s a 6·s

If 3mm < s < 4mm → R =2·s a 4·s

Anything falling off these ranges can produce conforming problems as mentioned.

Sheet metal thickness

When performing a drawing, it is essential to guarantee the constancy in thickness throughout all the piece. Having a perfectly constant thickness is impossible due to the complex state of tension of the piece, but it is commonly known that the constant the thickness remains, the better the drawing process was conducted.

Anisotropy of the sheet metal

Another essential aspect is to understand that the metal sheet that comes from rolling is not isotropic, since in the rolling process it was compressed in the vertical direction changing the shape of the grains and making it anisotropic.

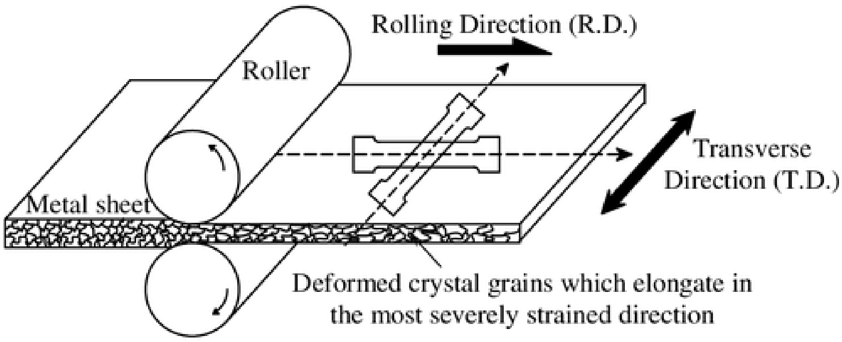

Figure 25: Anisotropy of a metal sheet after rolling. [14].

This anisotropy means that the sheet has different properties depending on the direction, which implies that for the same stress, it will not elongate the same amount in the transverse direction that in the rolling direction. This can have an important effect on the final geometry of the piece, causing undulations to appear.

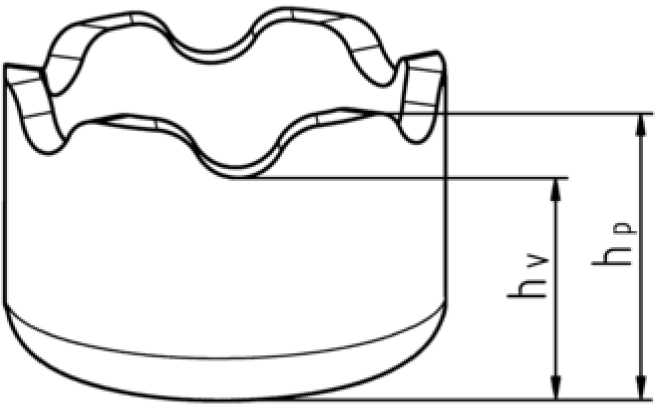

Figure 26: Effect of the anisotropy in deep drawing. [39].

If these undulations where to be removed after the process, there will be a considerable amount of scrap material with its corresponding cost. For this reason, it is important to avoid them in the process itself.

Sliding speed

Each material has its own optimal drawing speed, if it is too fast, there may be cracks, while if it is too slow, wrinkles may appear. For this reason, sometimes retention rings are used to slow down the sheet metal in the zones where it slides too fast. These rings generate friction between the tools and the sheet slowing it down.

Effect of the temperature

As mentioned in previous sections, the temperature has an important effect on the properties of the sheet metal, allowing greater deformations to occur without exceeding the rupture limit, and thus, increasing its conformability.

2.5. LUBRICANT

Lubrication is one of the most important aspects of the metal stamping process being its purpose to reduce friction between the blank and the tools.

High friction will lead to excessive wear, which will produce galling, scoring and cracking of parts. This leads to increased scrap, premature tooling wear and therefore, decreased profit. In other words, the lubricant is used to protect tooling from excessive wear and ensure that the tools produce high quality parts with the minimum maintenance cost, while averting the interruption of the process.

The most used lubricants for each material are the following:

- Steel: oils
- Copper and brass: water mixed with soap
- Zinc, tin and lead: mineral oil and graphite
- Aluminium: Vaseline and graphite

2.5.1. LUBRICANT APPLICATION

The lubricant should reach all the critical areas of the die and with equal importance, the lubrication system should ensure that the rate and flow of lubricant remains constant and adequate from the first stamped piece to the last one. A precise lubricant application method will make the stamping process repeatable, so careful consideration of the application method is a must.

On the other hand, an imprecise lubricant application method will produce a spotty lubrication, producing wear on some critical areas of the die, and reducing the quality of the parts manufactured. In addition, the methods which apply an excessive amount of lubricant or apply it in non-critical spots are also detrimental, not only because of the waste of lubricant but also because of the extra part cleaning costs.

There are two main methods of lubricant application, contact and non-contact. Both have some pros and cons so choosing one or the other usually depends on the application and the type of part that should be manufactured.

Contact methods as the name suggest consist on applying the lubricant with direct contact on the surface of the metal sheet. This produces a neat and consistent application with an assumable cost, but it touches the material so it can only be applied to smooth and flat surfaces.

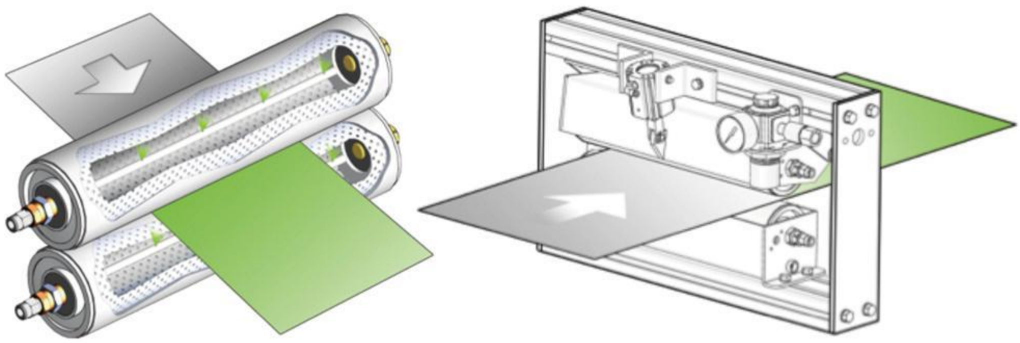

Figure 27: Lubricant application using rollers. [20].

Figure 27 shows 2 rollers with many little holes that provide lubricant to the sheet metal's surface. Although this is a very common method, there are others, like submerging the material into a lubricant pool.

The non-contact methods imply using a spray as the mean of application. The main benefits are that only the lubricant touches the material, and that it has a low cost and is easy to implement. On the contrary, it may produce an overspray mess or it can be inconsistent if the spray management system is not properly programmed.

Choosing the right system requires taking into account many factors, which are the rate at which the press is running, whether it is running coil or blank stock, the width and thickness of the material, the automation and monitoring needs, and the lubricant that will be used and how it will be supplied to the lubrication system to refill it.

2.6. STAMPING PROBLEMS

Identifying part defects should be pretty easy. These can include splitting, cracking, nonconforming part geometry, wrinkling, loose metal, under-strained parts, excessive burrs, scratches, dents, slug depressions, galling, and score marks.

Some of these problems can be easily identified in the simulation stage (see *Section 2.7*), which reduces the cost of making a new product.

This section will show the most common causes of each problem for every operation: punching/blanking, bending and drawing.

2.6.1. DEFECTS IN BLANKING AND PUNCHING

As explained in *section 2.5.2* the most common defect while conduction punching or blanking operations is the production of burrs. These are produced usually because of a bad adjustment of the clearance between the punch and the die, or because of these tools not being able to maintain constant this clearance or ever because they get worn over time.

Although that is the most common defect, there are others, like tears, shavings or the breakage or the tools.

The appearance of tears is usually due to similar reasons to the burrs. Because of an excessive clearance between the tools, or because they are not centred correctly or even they get worn.

In the case of the shavings, the cause is rather different, since they usually appear when there is a bad lubrication or the metal is too hard.

Finally, the tools might break if there is buckling, if they are not sharp enough, if the punch is too thin or if it is not centred correctly with respect to the die.

2.6.2. DEFECTS IN BENDING

After conducting a bending operation, many factors can produce several defects.

One of the most common ones is not meeting the dimensional requirements due to not having taken into account the springback. So, in every single case, this elastic recovery should be calculated and compensated.

Another common mistake is to bend the sheet in the wrong axis direction, since the bending axis must not be parallel to the rolling direction because of the anisotropy of the sheet metal. Otherwise, cracks might appear and if the sheet is bent over a sharp angle, it can break easily.

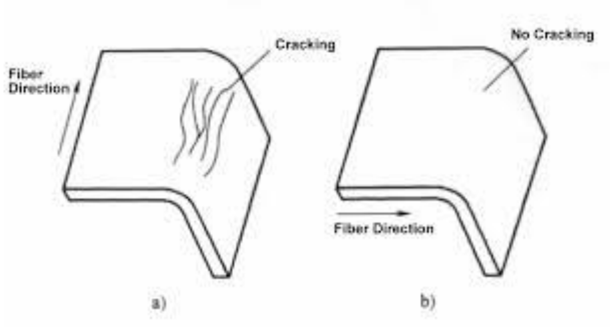

Figure 28: Fiber direction influence on cracks formation. [31].

Another important defect is the inconsistency of the thickness. Thin sections in the curves can be produced because of low bend radius, excessive bend angles or a wrong clearance between the punch and the die.

2.6.3. DEFECTS IN DRAWING AND DEEP DRAWING

One of the most common defects in this case is the undulations produced in the pieces after deep drawing because of the planar anisotropy of the sheet metal. This can generate high quantities of scrap which have an important impact in the cost.

Another common problem is the appearance of cracks and fractures. This can be due to several aspects, as having very sharp edges on the tool's surface, setting an excessive speed or not having a perfectly centred punch through all the operation.

Another problem is the possible breakage of the piece due to residual tensions. The deep drawing operation induces high amounts of residual tensions which then, a slight change of temperature of some charge applied to the piece can cause the propagation of cracks ending with the complete breakage of the piece.

2.7. STAMPING BENEFITS

With no doubt, there are many benefits of using metal stamping for a wide range of applications.

The accuracy is an important factor for many components, metal stamping can provide the precision needed along with a high quality at a lesser price.

High consistency is important in mass production and it can also be achieved by controlling the entire process, from the design with CAD software, proper tooling, professionally operated machines and a quality control for each piece to ensure its consistency.

Metal stamping is also appropriate for making large quantities of a product. Because of the tool's cost, this process is not appropriate for small batch quantities, but it is very cost-effective for mass production. Stamping machines are relatively easy to automate and can use high-end computer control programs that provide high precision, fast production and quicker turnaround times. This last factor also lowers the cost of labour.

2.8. STAMPING PROCESS SIMULATION

The metal stamping simulation is a nonlinear problem in which the material behaviour doesn't follow a linear model. In this case, the loads produced by the press induce a permanent deformation in the piece, so not only the elastic portion of the materials should be considered, but also the plastic one.

This non-linearity makes the calculations more complicated and heavily time dependant. And that makes it necessary to collect the stress-strain data from the metal during plastic deformation up to the point of failure.

To make this problem even more difficult, the plastic deformation must be limited to the maximum that the material allows, otherwise failure will occur. For this reason, simulating this process gives the necessary information to understand if it induces an excessive strain or splits the piece. With that information, changes can be made to the design of the piece, tools or process in order to improve the stamping operation and produce a high quality piece.

3. CONTROL ARM

3.1. CONTROL ARM DEFINITION

The control arm is the metal part that joins the chassis and the suspension. Their shapes and sizes depend on the vehicle they are assembled and they are commonly known as wishbone or 'A' arm. Though they are not known by the majority of the population, they are a crucial component of any car. For creating a visual map of their placement and geometry see *Figure 29*, where the control arm can be easily spotted under the car's suspension on either side. Notice that the wishbone of the figure has an 'L' shape, but that is not the only type, the current different types of control arms will be shown in *Section 3.3*.

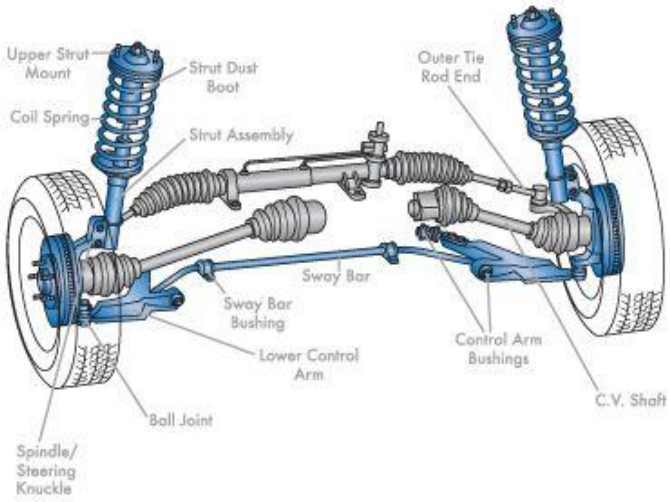

Figure 29: Parts of the suspension of a front wheel drive car with MacPherson strut. [26].

On the chassis side, the control arm is hinged in bushes, called control arm bushes. This allows rotation around the axis they are mounted. On the wheel side, the wishbone has a ball joint which serves as a pivot point for the steering knuckle, allowing the rotation in all axis. This way, the component is able to move up and down and rotate in all axis on the wheel side, which is essential in order to steer and damp the oscillations produced while driving.

Notice that the control arm is not hinged directly to the chassis, but by means of bushes. This is essential so it reduces the vibrations dampening them with the rubber of each bush.

3.2. CONTROL ARM FUNCTION

The control arm serves different purposes, being the main one that they provide a structural support for the steering knuckle (*Figure 30*).

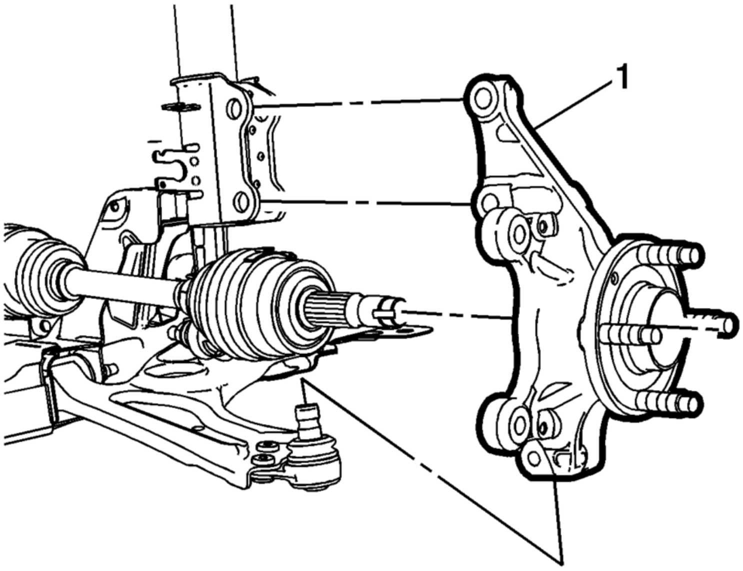

Figure 30: Steering knuckle assembly of a front wheel drive car. [8].

Figure 30 shows the assembly of the steering knuckle (indicated as part 1). Looking at the figure it is easy to realise how important it is the control arm, since the ball joint provides not only a support for the steering knuckle, but also a pivot to rotate in all axis. That is important because when steering, it is the steering knuckle that turns, which is attached to the wheel hub by bolts and this last part is also attached to the wheel by bolts.

But if the control arm was to restrict the vertical movement of the steering knuckle, the chassis would be joined with the wheel and it would be impossible to absorb any oscillation produced by the road, in other words, the suspension would become completely useless. That is the reason why on the chassis side it is hinged and not welded or fixed by any other method, since this way, the other control arm end can move up and down with a movement such as the one of a lever. This degree of freedom allows the assembly of the spring and damper to absorb all vibrations produced.

3.3. CONTROL ARM DESIGNS AND ASSEMBLIES

Some vehicles have 2 control arms on either side, others only one, and high end automobiles have them on the rear axle. There are also different geometries and sizes, so in this section it is shown the different kinds of wishbones that are currently used in the automotive industry.

Wishbones can be classified depending on their geometry in three categories: A-Arm, L-Arm and Adjustable Control Arms.

3.3.1. A-SHAPE ARM

As it is noticeable in *Figure 31*, A-shaped arms are similar to a triangle and have two bushings on the narrower ends to hinge to the car's frame and a ball joint on the middle. This is the most common geometry nowadays and it is used in a variety of cars.

Figure 31: A shaped control arm. [38].

3.3.2. L-SHAPE CONTROL ARM

L-shaped control arms are really similar to the 'A' ones, they also have 2 bushings on the frame side and a ball joint on the other end. The only difference is that the ball joint is not placed in the middle as it is appreciable in *Figure 32*.

Figure 32: L-shaped control arm. [1].

3.3.3. ADJUSTABLE CONTROL ARMS

Some control arms have only one bushing on one end and the ball joint on the other, and are also adjustable in length as it is shown in *Figure 33*.

Figure 33: Adjustable control arms. [29].

This type on control arm is used to adjust wheel camber, if the length of the control arm is increased, the wheel will be lean inwards, and a lower length will lean the wheel outwards (see *Figure 34*).

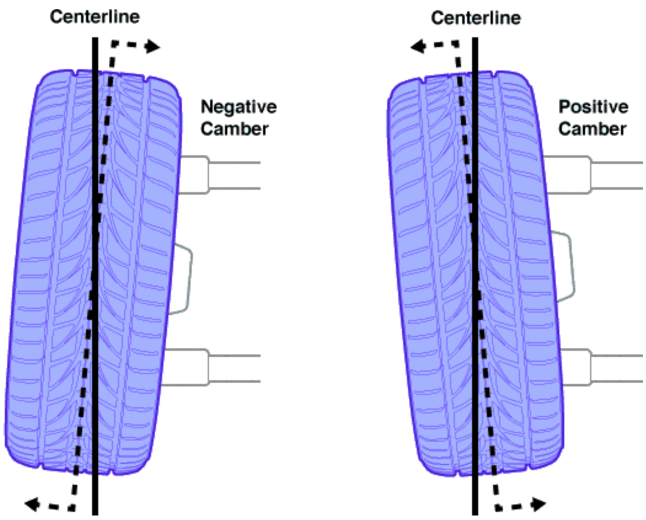

Figure 34: Positive and negative camber adjustment. [21].

A properly adjusted camber means even tyre wear and better traction, furthermore, the design makes the control arm lighter, increasing driveability and handling. However, because of their design and purpose, this type of control arm is used only in motorsport vehicles.

3.3.4. ASSEMBIES

For many years' cars had two control arms on each side of their front end, the upper and lower one. But that changed with the introduction of the MacPherson suspension, which has a strut to support the weight of the car. Hence, most cars have rid of the upper control arm, therefore enlarging the periods between services.

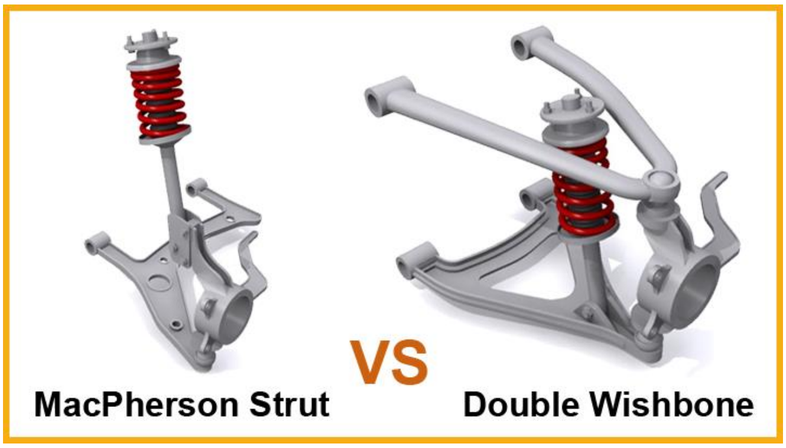

Figure 35: MacPherson Strut vs Double Wishbone. [16].

3.4. CONTROL ARM MATERIALS

There are three materials with which control arms are manufactured: cast iron, steel and aluminium.

3.4.1. STEEL CONTROL ARMS

Steel is the most used material for this part along history since it reduces the manufacturing cost allowing mass-production. Besides, steel flexes under stress, and that is a great advantage for a suspension part like this one. Its high strength is also an important factor to take into account, since it reduces the cases of breakage or cracking.

On the other hand, this component is situated near the ground and it is exposed to the atmosphere. That is the perfect combination for building up corrosion on the piece surface. Thereby, steel control arms have a reduced lifespan. Another disadvantage is reducing the driveability and handling of the car because of the increased weight compared to other materials such as aluminium.

3.4.2. ALUMINIUM CONTROL ARMS

Aluminium control arms are lighter than steel ones and that results in easier steering. One of the biggest advantages is that aluminium does not rust, when exposed to the atmosphere, the external layer oxidizes at a very fast rate producing a hard layer of oxide that prevents the piece from deteriorating and rusting. Moreover, the control arms are made of cast aluminium and because of their geometry, which is a bit sturdy, they can resist high loads applied to them.

Even though it has some important advantages, it also has some disadvantages that should be taken into account. The main ones being the low capability to flex under stress and its softness, which translates in a higher likelihood of breaking under impact or stress.

3.4.3. CAST IRON CONTROL ARMS

Cast iron control arms are used in heavy vehicles, like trucks and SUVs, so because of the increase in popularity of SUVs, the cast iron control arms are becoming more and more used in modern vehicles. Even though these arms are lighter than the steel ones because of their narrower design, they can withstand high weights.

4. CONTROL ARM SCAN AND DESIGN

For the purpose of this academic work, a control arm property of EPSEM has been used.

The features of this control arm are:

Material: Stamped steel

Geometry: L-shaped

Compatibility with car models: Volkswagen Polo V.

The first step was to 3D scan the control arm to obtain a 3D model to work with. Then, with the 3D model, it will be easy to design the tools.

4.1. OBTAINING THE 3D MODEL

In order to obtain the 3D model, a 3D scanner has been used, specifically the model Sense 2 from 3D Systems. This scanner has 3mm scanning precision and 1mm detail resolution which should be enough to obtain an accurate model of the real piece. One of the major difficulties scanning was that the piece is black-tingled, which means having a low-reflective surface. This issue was solved by covering the piece with white powder (see *Figure 36*) so the waves generated from the scanner could reflect and be detected properly.

Figure 36: Control arm ready for scanning.

Once the model was completely scanned, the geometry had to be refined and its surfaced smoothed. This part was carried out using the software Blender, since it has a tool for detecting the surfaces and building a custom mesh very similar to the scanned geometry (see *Figure 37*).

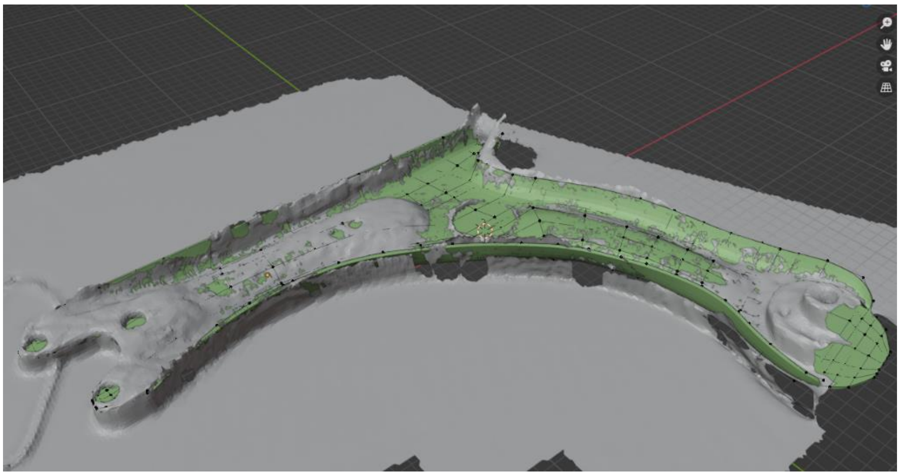

Figure 37: Refined mesh overlaid with the scanned geometry.

Once this step was completed, the geometry was exported in a STL file and imported in Catia V5, where a surface model could be created and converted into a solid body (see *Figure 38*).

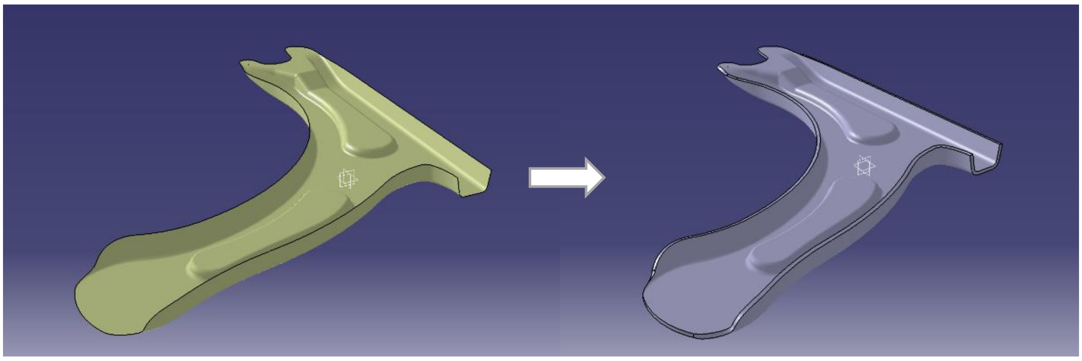

Figure 38: Surface model to solid body conversion.

Even though the measured thickness of the real piece is around 3mm, the solid conversion was performed giving the surface a thickness of 3,2mm, since a little margin is needed to stamp the metal sheet correctly, and the external surfaces of this model are the ones of the die (lower side) and the punch (upper side).

With the geometry of the 3D CAD model finished and looking very similar to the real part, the last step was to ensure that its dimensions met the real ones by scaling the model till achieving this goal.

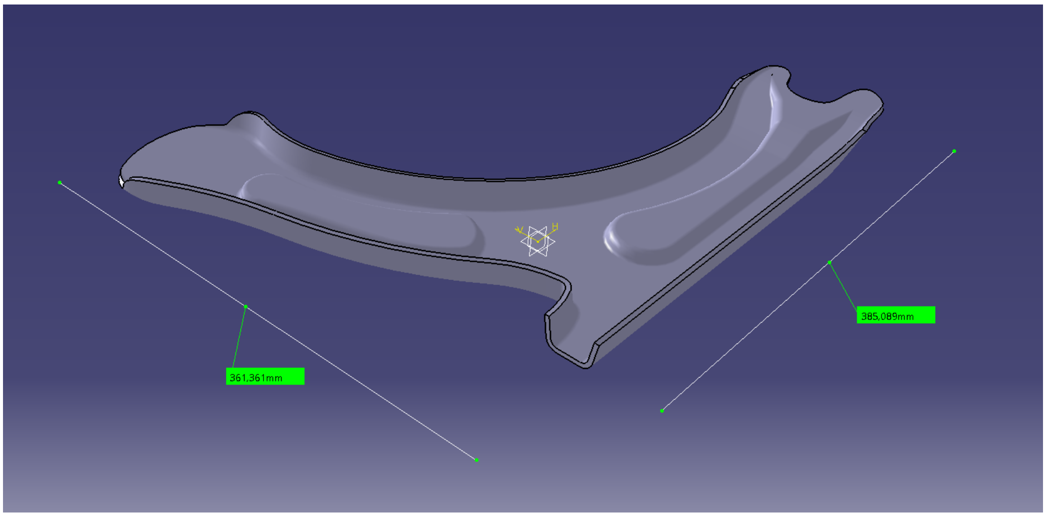

Figure 39: Dimensions of the designed control arm.

After doing this step, *Figure 39* shows that the dimensions are around 385mm long and 361mm wide. Comparing to the real ones, which are around 380mm long and 370mm wide, there is little difference, that can be attributed to the scanning and modelling process.

Being this the final geometry of the control arm, the following step would be the design of the blank.

5. BLANK DESIGN AND BLANKING PROCEDURE

With a higher difficulty, the sheet metal should be given an initial geometry, the blank. This geometry can produce problems of convergence in the simulation and non-conforming problems in real life if it is not designed properly.

For simulation purposes, the geometry should satisfy some requirements:

- There shouldn't be sharp edges, since those can produce convergence problems.
- The geometry should avoid an excessive stretching which could induce a reduction of the thickness.
- The shape obtained after deformation should be similar to the one of the piece.

In order to start with the simulations, the outline of the sheet metal will be initially designed with a 20mm offset from the piece outline. But after analysing the simulation, the shape of the sheet metal will be optimised to get a more precise geometry and avoid conforming problems in some critical areas.

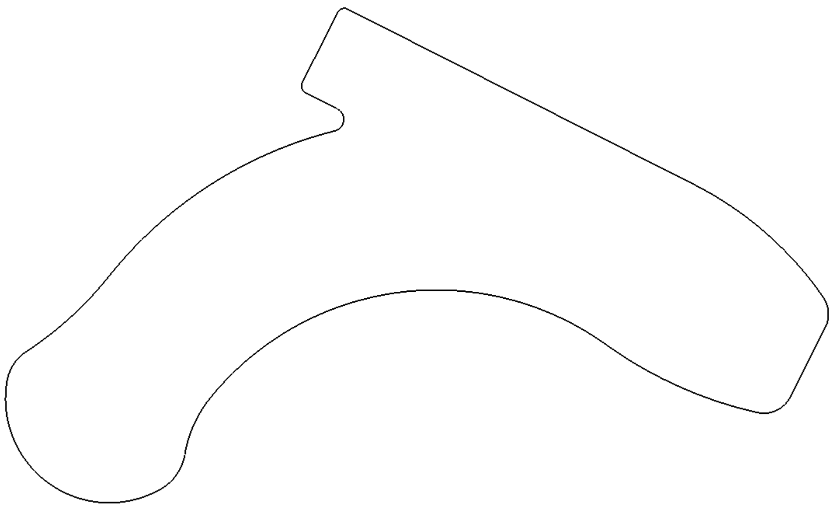

Figure 40: Blank's initial design.

5.1. BLANK DISPOSAL AND MATERIAL EFFICIENCY

In order to obtain the blank, a blanking operation should be performed. As stated in section 2.4.3, the position of the blank can have multiple effects on the amount of scrap material and also on the possible defects of this piece due to the anisotropy of the sheet metal.

From the mentioned section, it is known that a very common distribution for pieces that fit in a triangle is the oblique disposal. Also, the bending axis' in this display are not parallel to the rolling direction which will decrease the likelihood of failure. For these reasons, the blanks will be displayed in an oblique disposal.

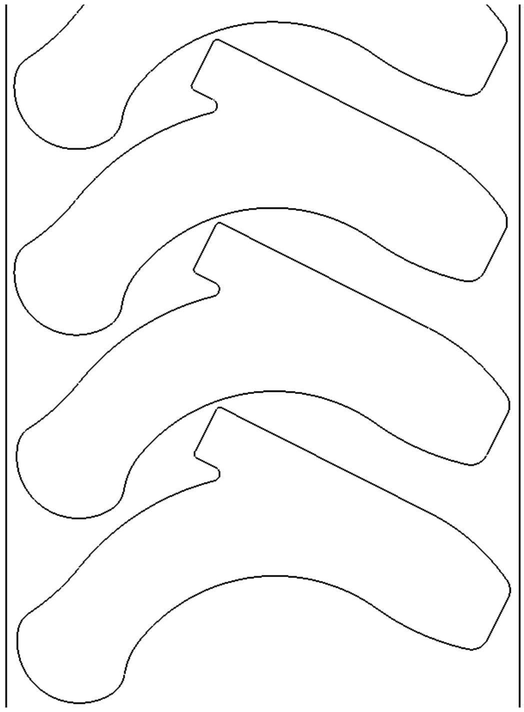

Figure 41: Disposal for the blanking operation.

Knowing that the intersection points are punctual, a separation of at least 1 thickness between pieces and between each piece and the boundaries of the sheet metal is assured.

As mentioned previously, the thickness of the sheet metal will be 3mm since this is the dimension measured from the real control arm that is under study.

Moreover, the material efficiency is an important factor that should be taken into account, as such, it is going to be calculated below:

$$r = \frac{S_{blank}}{S_{used}} \cdot 100\%$$

To find the values of S_{blank} and S_{used}, Catia V5 will be used, since it can provide the measures needed.

$$r = \frac{76643.21}{200{,}92 \cdot (555{,}45 + 3 \cdot 2)} \cdot 100\% = 67{,}94\%$$

That value is good enough and since it provides the right bending axis' this will be the disposal selected for production.

5.2. BLANK PROPERTIES

The blank is the only part of the simulation that will be assigned a material, since the tools will be defined as 3D discrete rigid so they don't suffer any deformation. This will save time and computational effort.

The material that is going to be used for the simulation is a steel with a high degree of formability, so its properties will be the following ones:

- Density: 7850 kg/m^3
- Young modulus: 200.000 MPa
- Poisson's ratio: 0,3
- Elastic limit: 91,29 MPa
- Rupture stress: 521,29 MPa
- Thickness: 3 mm

Its curve of stress-strain is the following one:

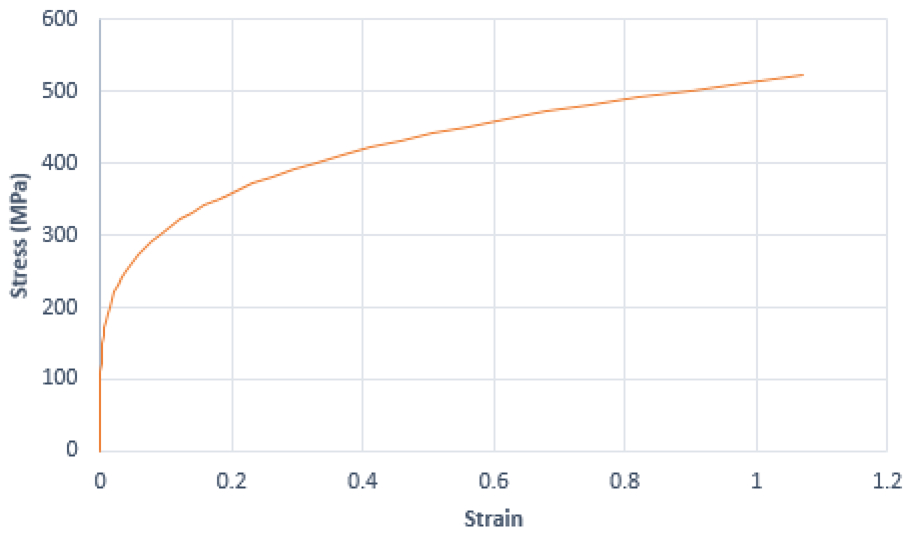

Figure 42: Stress-strain curve.

6. SIMULATION SETUP

This is a critical step upon the simulation of the sheet metal's plastic deformation process, since many variables can have different effects on the simulation itself.

To perform the simulation, *Abaqus CAE 2020* ® software will be used, since it is user-friendly and it has all the tools needed to obtain and analyse the results.

The first step will be importing the parts to the *Abaqus* module and setting their type. In this case, the die, the punch and the holder have been defined as a 3D discrete rigid shell, while the metal sheet has been set as a 3D deformable shell.

That means that the tools won't suffer any deformation, which will save a lot of time since the software won't have to compute the displacement of every single node of the tools.

For this reason, the only material that should be created and assigned is the one of the sheet metal, with the properties mentioned in *section 5.2*.

Following this step, the type of analysis should be set, while initially a static (implicit) analysis was used, further simulations required a dynamic (explicit) analysis, which usually is able to compute more complex simulations that are highly non-linear.

In the next step, the interactions between the different parts should be assigned. For the upcoming simulations, the interaction between die-blank and punch-blank will have both a normal behaviour and a tangential behaviour, with a friction coefficient of 0,01 (assuming a good lubrication, which is essential for the process). The holder will have only a tangential behaviour, also with a friction coefficient of 0,01, since its only purpose is to guide the blank letting it slide to fit in the die.

After that, some boundary conditions should be applied. On one hand, the die and the holder will be completely fixed. On the other hand, the punch will descend a certain value to perform the operation.

Finally, the last step before launching the simulation is the meshing. To have good results, it is important to have a good quality mesh. That is why all the tools have been meshed with a fine mesh of 4mm element size and the blank has been meshed with 2mm element size.

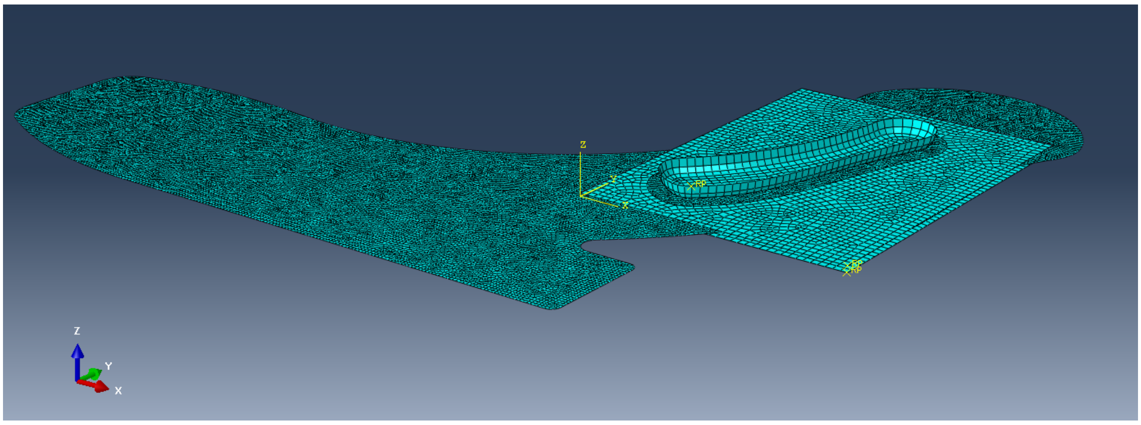

Figure 43: Mesh of the tools and the blank for the first simulation.

This gives a total of 23254 elements for the blank, 2336 elements for the die, 512 elements for the punch and 1634 elements for the holder. However, these values will increase considerably in the simulations with the complete tools.

After some tries, this size and element type has given good results in terms of an equilibrium between the computation time and the convergence of the results, so those will remain constant through all the simulations.

7. SIMULATIONS AND ANALYSIS OF THE RESULTS

This is the core section of the project, where simulations using *Abaqus CAE* will be carried out and its results analysed. After each simulation, conclusions will be extracted to improve the geometry of the tools, the blank or the process itself.

The tools will have the negative shape of the control arm, but after analysing the results, some slight changes will be done.

7.1. SIMULATION OF THE BUMP

After carrying out many simulations, there were many convergence problems when the sheet got to one of the bumps, so in this case, only the area indicated in *Figure 44* in red will be deformed to determine the cause of these problems.

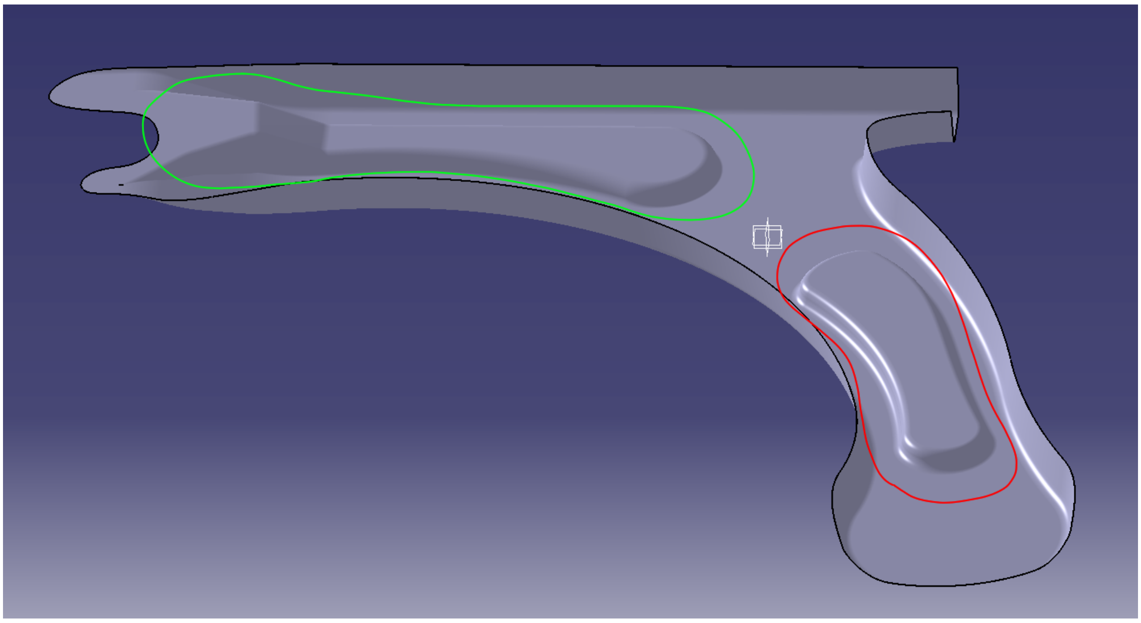

Figure 44: Bump to analyse in this section's simulation.

In this case, only the part of the tools' corresponding to the inside of the red line were designed as well as the holder. So, after all the design process, the simulation was launched and the results were the following ones.

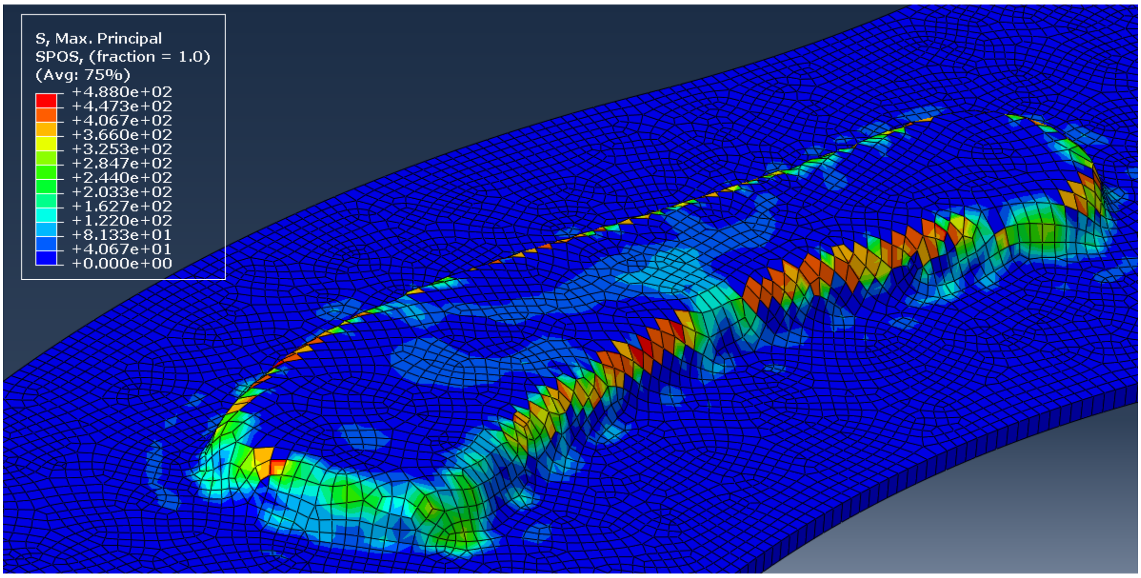

Figure 45: Maximum principal stress on the bump zone (MPa).

Looking at the maximum principal stress, it is easily appreciable that all the outline of the upper part of the bump is at approximately 488 MPa which is a really high value. However, the low level of continuity throughout the entire outline is the key point that most likely causes the convergence problem.

As shown in *Section 2.4.5*, the cause of this is likely because of a very sharp edge. In this case, the sharp edge is on the punch's surface, measuring less than 0,5mm in radius.

From the mention section, it is known that the minimum radius can be calculated as:

$$R = 0{,}8 \cdot \sqrt{(D-d) \cdot e}$$

Though in this case the direct dimensions are unknown, the following relation can be used as an approximation:

$$D - d = difference\ in\ length\ between\ the\ die\ and\ the\ punch$$

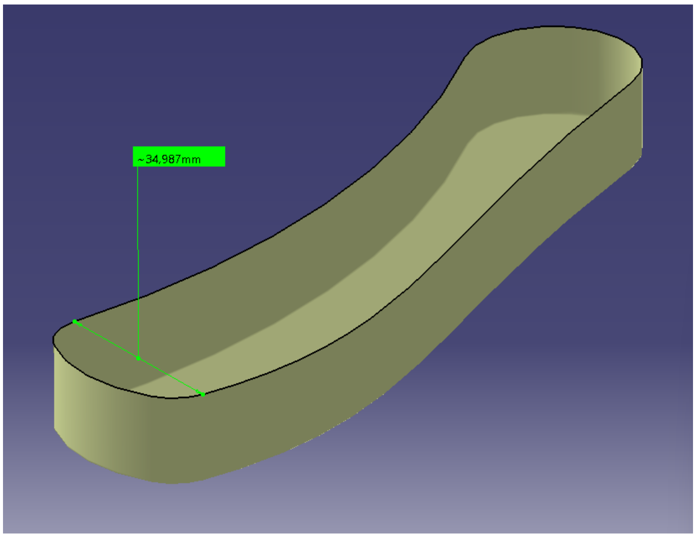

Figure 46: Punch transversal dimension (mm).

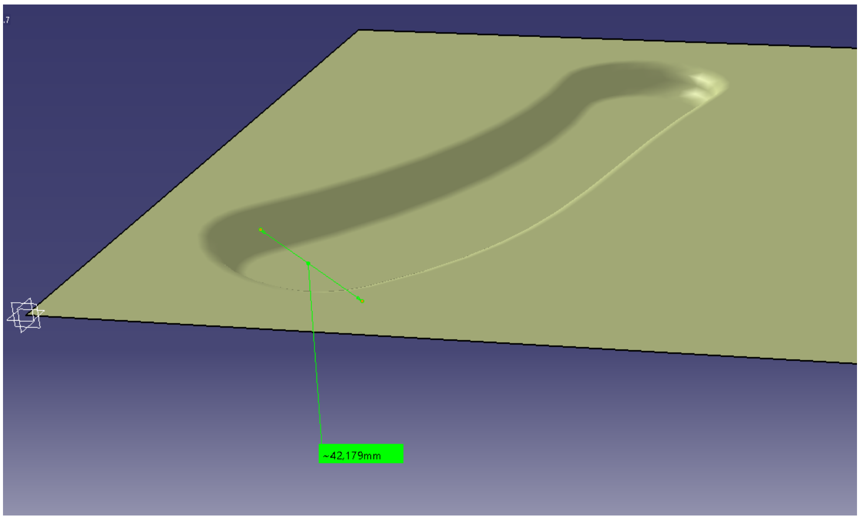

Figure 47: Die transversal dimension (mm).

With this data, it is already possible to compute the minimum radius of the punch:

$$R = 0{,}8 \cdot \sqrt{(42{,}18 - 34{,}99) \cdot 3} = 3{,}72mm$$

So, to ensure that there is a little margin, the next simulation will be carried out with a radius of 5mm on the punch.

After the changes are made to the punch's geometry, the simulation is launched again with the following results:

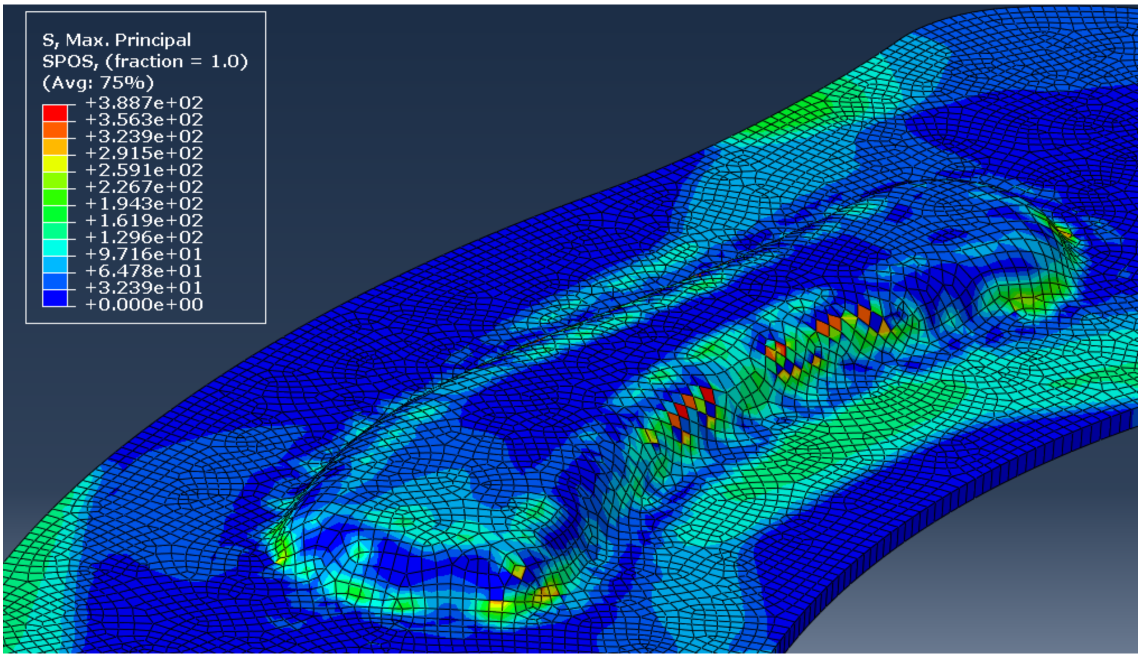

Figure 48: Maximum principal stress on the bump zone (MPa).

From *Figure 48*, it is easy to appreciate the difference, since in this case the outline of the upper side of the bump at maximum stress has almost disappeared. This is because the sheet in the previous simulation was bent with an excessively low radius, which could easily result on the failure of the piece. On the contrary, in this last simulation, with a considerably higher radius, the piece does not reach the rupture stress limit at any point.

The information extracted from this simulation is very useful since it can be easily extrapolated to other areas of the piece, like the other bump shown in *Figure 44* in green, which also has a really low radius value that should also be increased in order to avoid the breakage of the piece.

7.2. COMPLETE SIMULATION

With the previous results in mind, the next step would be to simulate the control arm's deformation in one single movement of the press.

Due to the complexity, in this case the simulation will be dynamic explicit, which will allow the software to solve this highly non-linear problem. For this simulations, the tools have to be designed completely, as well as the holder (see *Figure 49*).

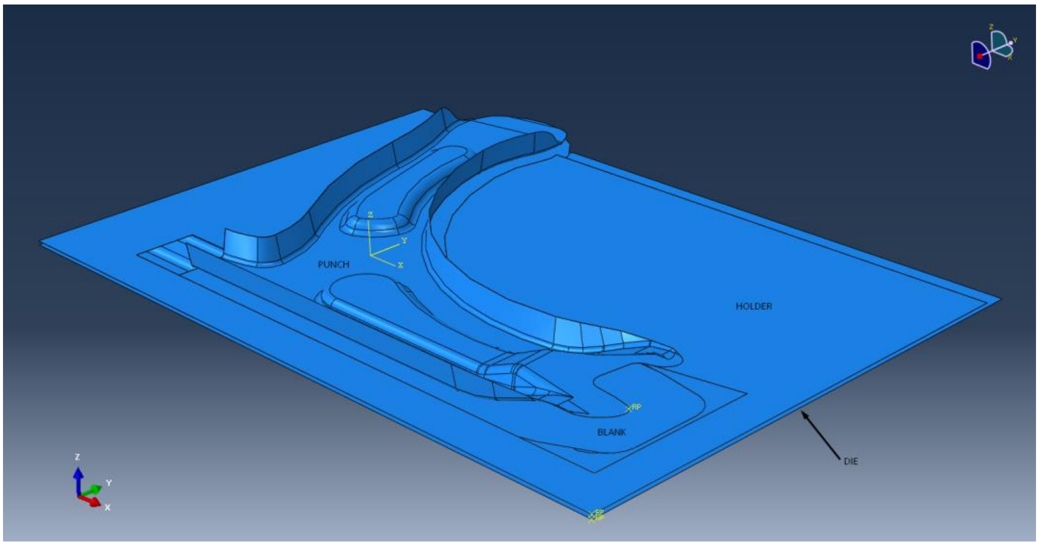

Figure 49: Assembly for the complete simulation.

In this case, the holder only guides the blank into the die by pressing some areas and not the complete perimeter of the blank. For this reason, at the point where the blank stops making contact with the holder, there could be some interactions which cause the simulation to stop.

In order to avoid that, the holder will guide the blank only at the beginning of the process, once the blank gets slightly into the die, the holder will rise to avoid any interaction. Thus, this simulation has two steps, one where the holder guides the blank and the punch descends 5mm, and another in which the holder rises and the punch continues to descend up to the bottom.

7.2.1. SIMULATION RESULTS AND ANALYSIS

Leaving the material properties of the blank identical, the simulation is submitted. But before analysing the results, it is a great idea to understand whether the results can be considered as valid or not.

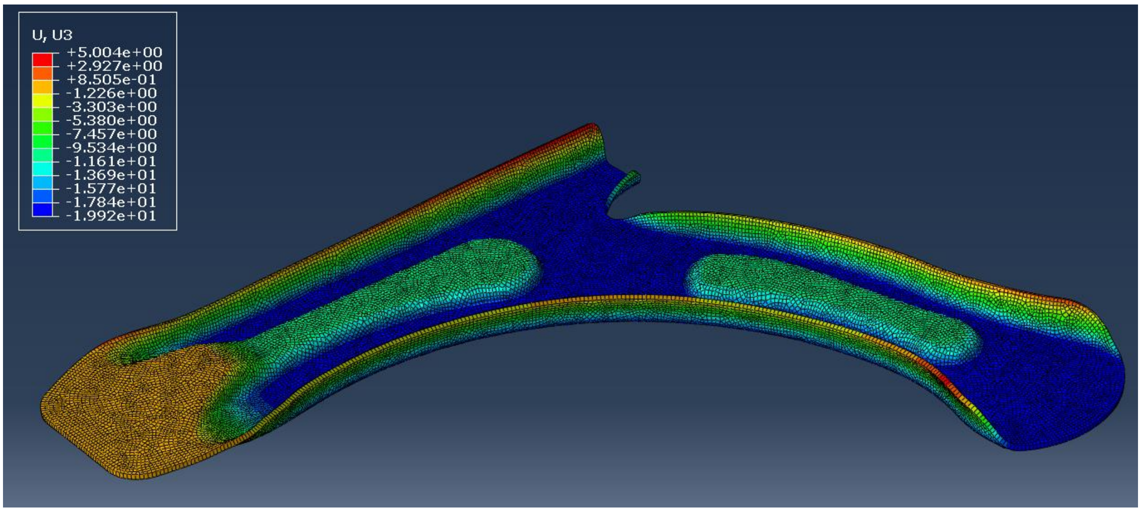

Figure 50: Vertical displacement (mm).

In the vertical displacement distribution (*Figure 50*), the red surfaces have descended approximately 20mm, which is the depth of the die. That shows that the computations were completed successfully and after analysing the total artificial energy of the simulation (7% of the total energy) the results can be considered as valid.

After this first step, the analysis of the obtained results commences.

- Von Mises stress distribution

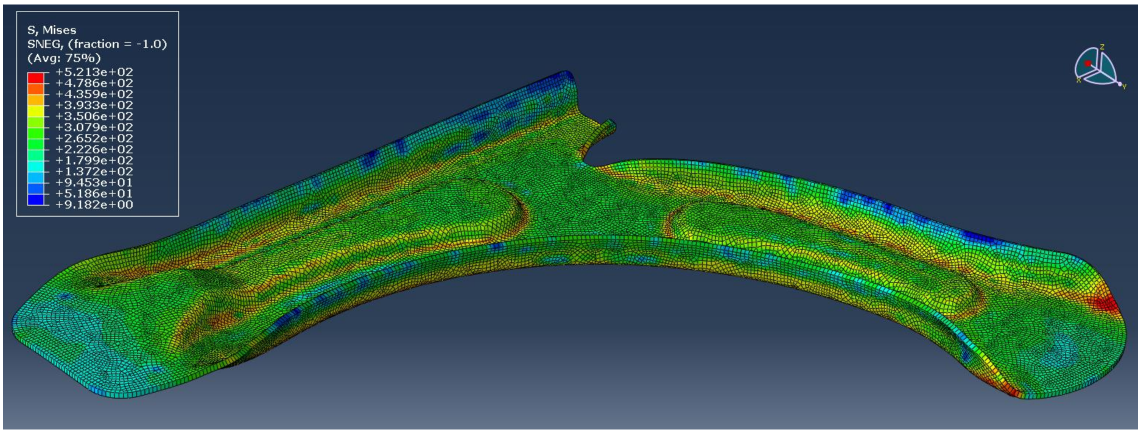

Figure 51: Von Mises stress distribution (MPa).

This figure shows that the elastic limit (91,29MPa) has been exceeded throughout all the areas of interest, which is good since that means that the operation has produced a plastic deformation on the sheet metal, changing its geometry permanently.

- Maximum Principal Stress distribution

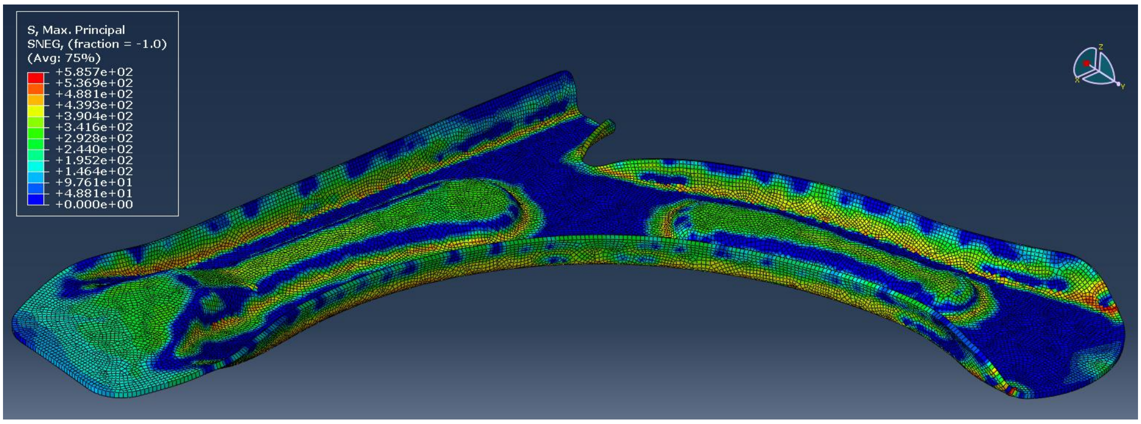

Figure 52: Max. Principal Stress distribution (MPa).

In *Figure 52* the maximum stress variable shows two zones on the right side of the piece where the rupture strength is reached. Those points are where most likely the cracks will appear and start to propagate causing the breakage of the entire piece.

In this case, it is easy to identify that the cause of this problem is both because of the small bend radius and the geometry of the punch (see *Figure 53*).

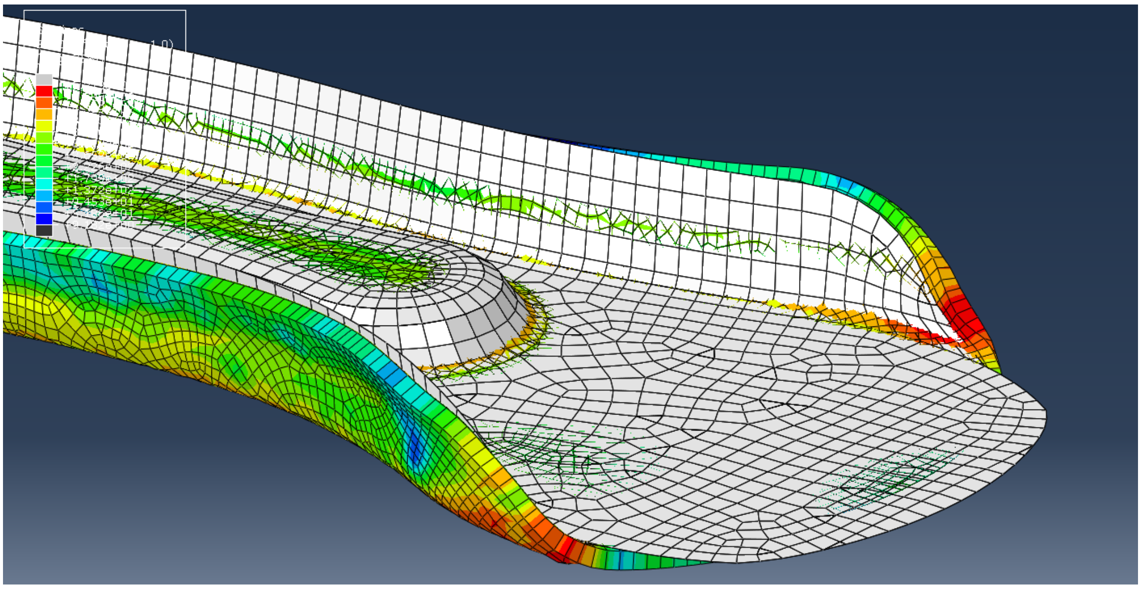

Figure 53: Punch geometry over the deformed piece.

The punch wall on both sides stops before the end of the piece, which creates a sharp angle where high stress is produced on the sheet metal.

Therefore, in the following simulation, the punch will have a more continuous geometry, as an attempt of reducing this effect.

- Plastic strain equivalent

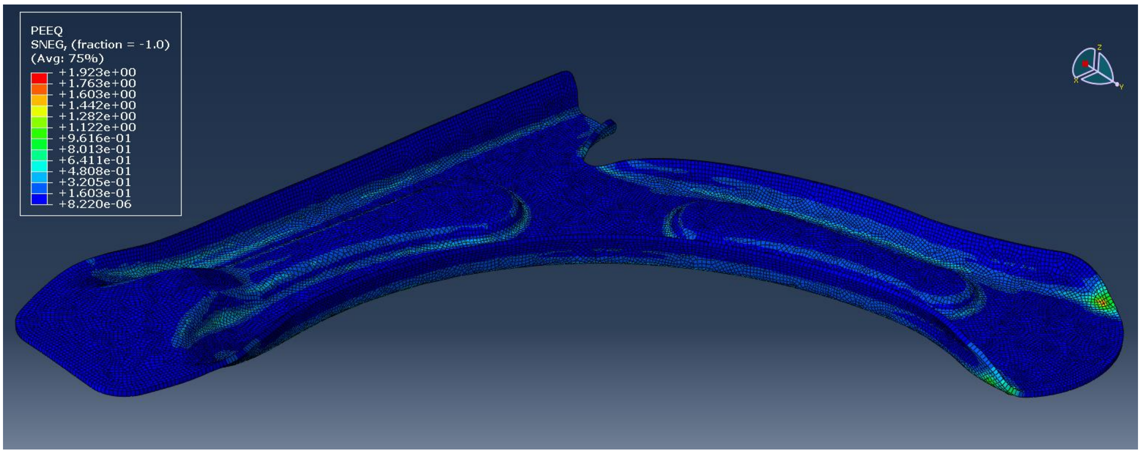

Figure 54: Plastic strain equivalent distribution.

To continue, the plastic strain equivalent variable (*Figure 54*) gives a really important information. All the areas of the same dark blue color have not suffered any plastic deformation, thus, those surfaces are ideal spots to make holes on the blank before the drawing operation, since they will not be stretched through the process. As *Figure 2* shows, all the holes of the real piece are placed throughout these areas.

Figure 2 (Rep.): Operations performed to obtain a control arm.

On the contrary, the rest of the areas have suffered important plastic deformations. Therefore, those spots are not ideal for making any previous operation, since the geometry will be stretched and won't remain constant.

Finally, the simulation's final result is quite similar to the real piece with some slight differences. The first one is that the height of the bottom wall is not constant and when it reaches the sharp angle curve indicated in *Figure 55*, it is almost inexistent. In the following simulation, the blank geometry will be updated to obtain a more constant wall height at that point.

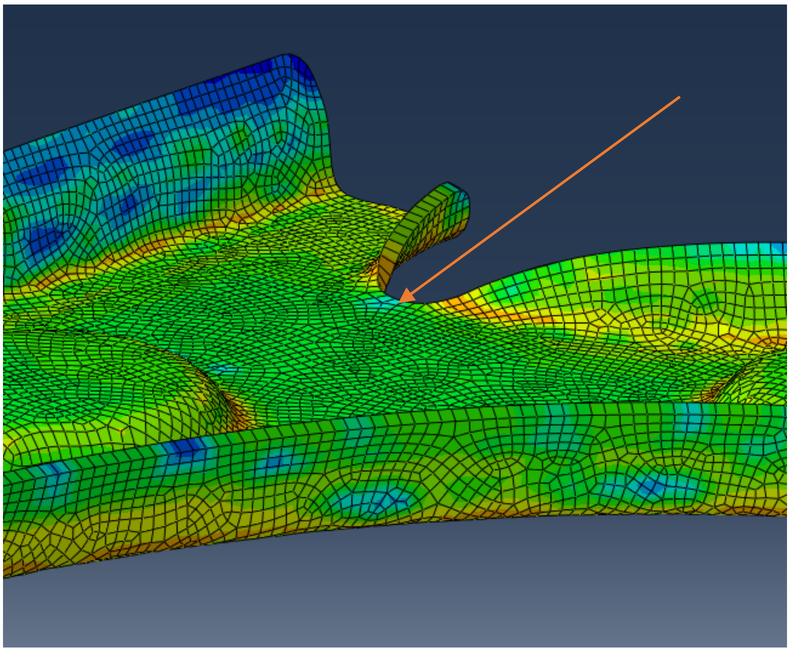

Figure 55: Sharp angle curve.

Another noticeable difference is that the shape of the piece on the left side is not the same as the real one (see *Figure 56*). For simulation purposes, the blank was designed with a straight line on that side instead of the real shape. However, the results show no plastic strain on that area, so it could be interesting to update the blank geometry to have the same shape as the real piece, since it should not be deformed by the operation.

Figure 56: Outline real shape.

Those are all the changes regarding the blank's geometry for upcoming simulations.

7.3. OPTIMISED SIMULATION

Once all the changes to both the punch and the blank are made, it is time to launch another simulation.

Apart from the geometrical changes made to the tooling there is another one really important that can give essential information of the piece's final geometry, the spring-back effect. An additional step was introduced at the end of the simulation. In this step the punch rises so it stops having contact with the sheet metal, thus letting the elastic deformation out and showing the effect of the elastic recovery or 'spring-back'.

7.3.1. SIMULATION RESULTS AND ANALYSIS

With all set up, the simulation is submitted, but before proceeding with the analysis, the validity of the results is determined.

This can be done by comparing the artificial energy with the total energy of the system, if the artificial energy (ALLAE) is below 10% of the total energy (ALLIE) the simulation results can be considered as valid.

In this case, as *Figure 57* suggests the artificial energy (red curve) does not exceed approximately the 2% of the total strain energy (blue curve), thus the results of the simulation can be considered valid.

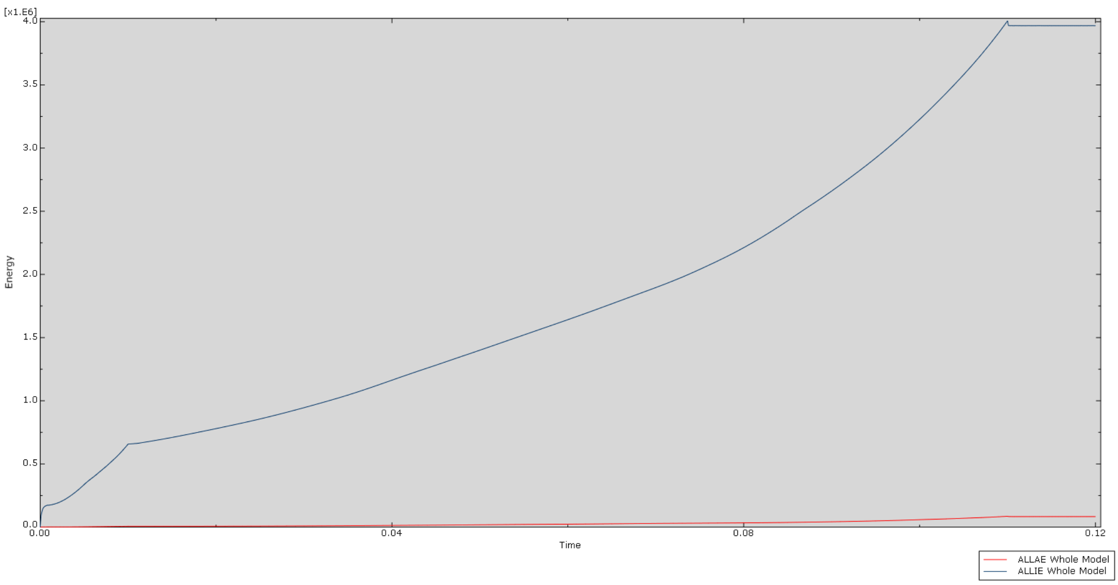

Figure 57: Artificial strain energy and total strain energy curves.

After this essential step, the results before the elastic recovery takes place are analyzed.

- Von Mises stress distribution

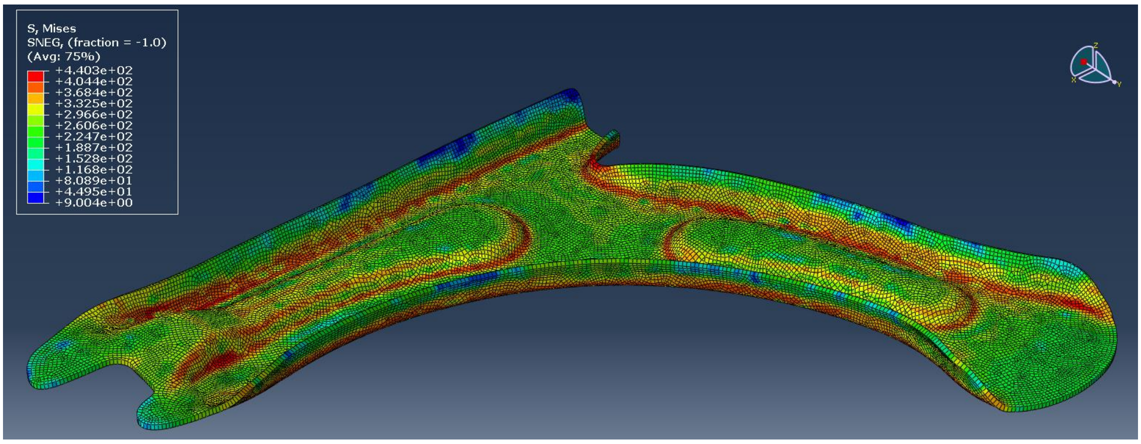

Figure 58: Von Mises stress distribution (MPa).

Starting with the von Mises variable displayed in *Figure 58* which ensures that the elastic limit has been reached on all the bends and the piece has been permanently deformed. The distribution is really similar to the one of the previous simulation, with the difference that the maximum value has decreased around 80MPa thanks to the changes made to the tools.

- Maximum Principal Stress distribution

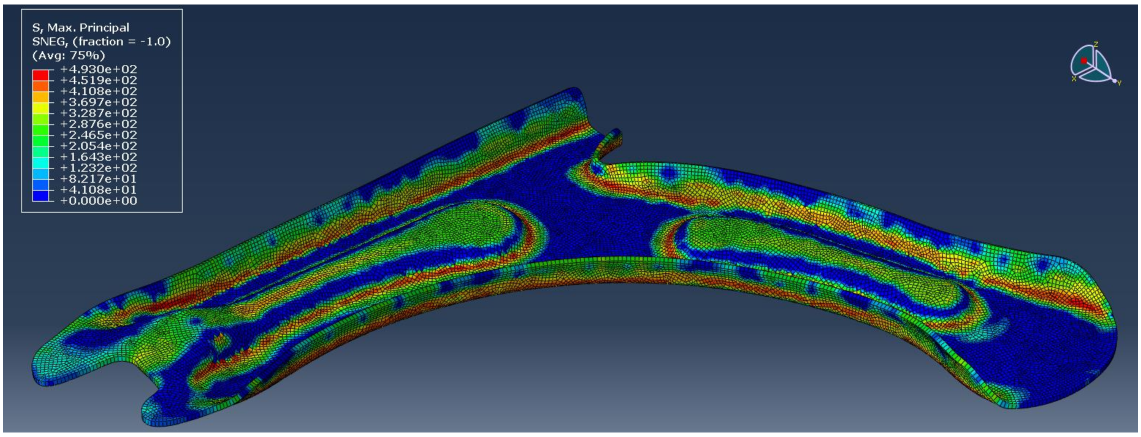

Figure 59: Maximum principal stress distribution (MPa).

The maximum principal stress distribution (*Figure 59*) shows an important improvement as well, the maximum level of stress (493MPa) does not reach the rupture limit (521MPa), thus, after the optimization of the geometry, the likelihood of failure has decreased considerably so the process can be carried out without breaking the piece.

- Total Displacement

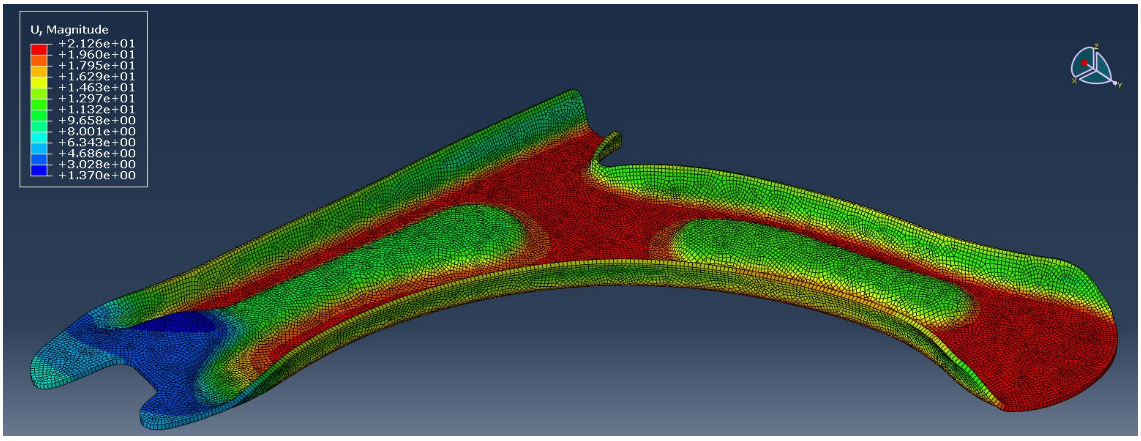

Figure 60: Total displacement (mm).

The total displacement of the piece offers important information about how much every element of the mesh has been displaced by the process. In *Figure 60*, it is easy to appreciate that the bottom of the control arm has been displaced around 21mm by the punch.

- Vertical displacement

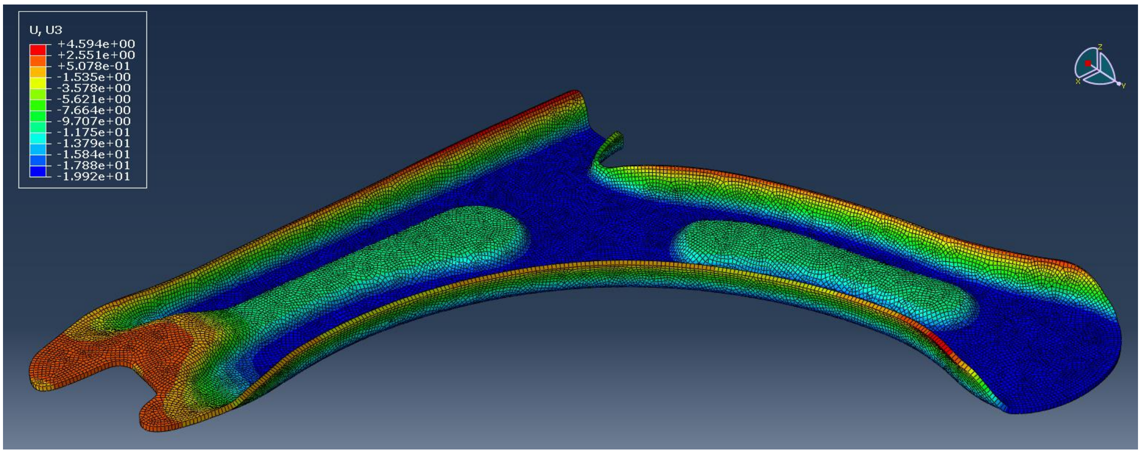

Figure 61: Vertical displacement (mm).

The displacement in every direction can be analysed so that the position of every element with respect to its starting position is known. However, the vertical displacement offers an essential information, whether the punch has descended up to the bottom or not. In *Figure 61*, the vertical displacement is around 20mm, and as mentioned previously, that is the depth of the die too. This is relevant because it indicates that the punch descended completely up to the bottom.

- Plastic strain equivalent

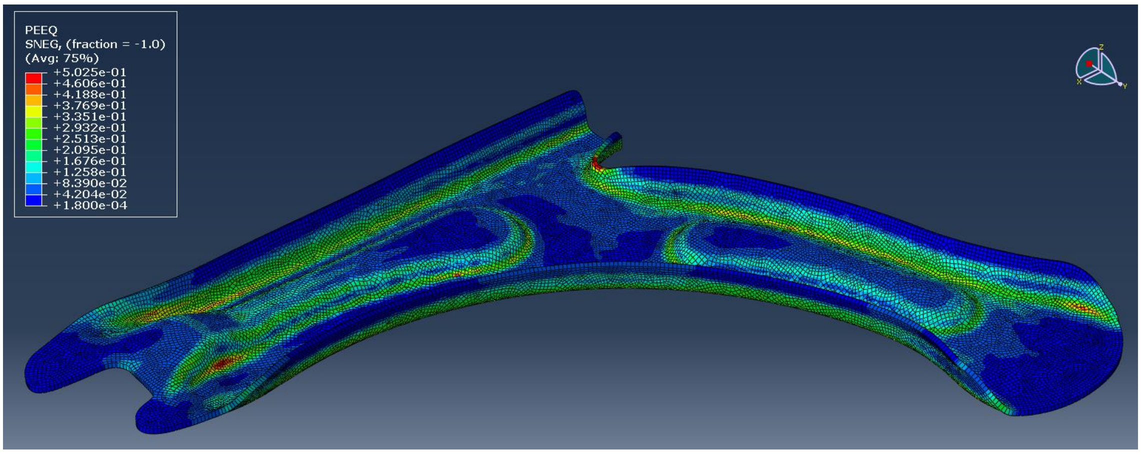

Figure 62: Plastic strain equivalent distribution.

The plastic strain equivalent shows the areas where there is plastic deformation. All the areas at a color other than blue have had at least a slight plastic deformation. This distribution offers the same information as the von Mises, but instead of showing tensions, it shows deformation.

- Thickness

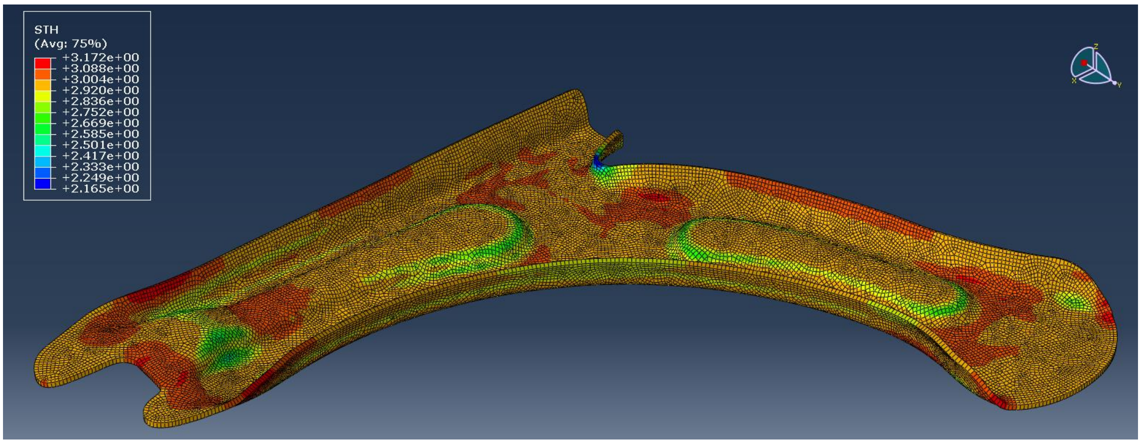

Figure 63: Thickness of the piece (mm).

Regarding to the thickness, as explained in *Section 2.4.5*, it should remain as constant as possible. Its constancy is a good indicator of how well the process of drawing is conducted. *Figure 63* shows that this constancy is maintained throughout the entire piece with very slight changes (+/-0,1) except at one point, the bend indicated in *Figure 64*, where it decreases considerably (≈0,8mm).

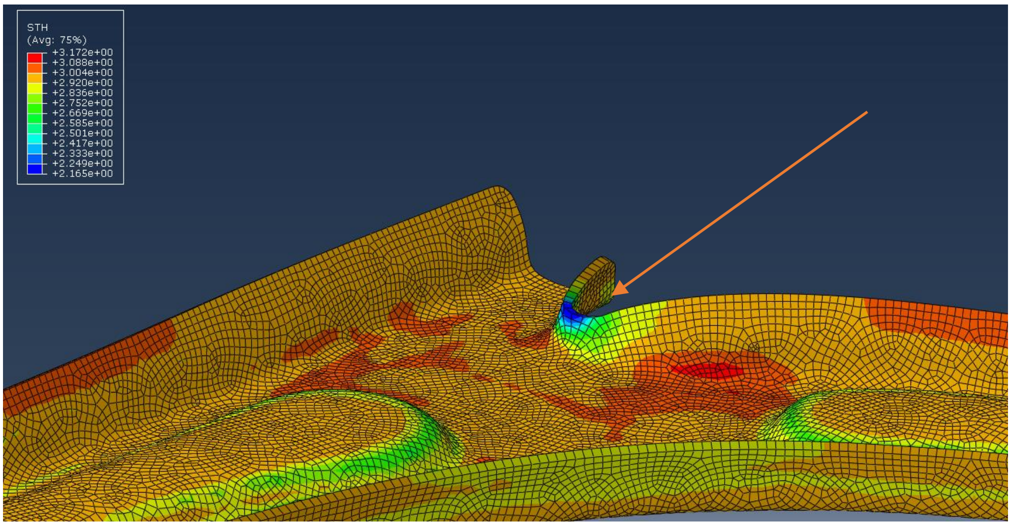

Figure 64: Thickness of the piece at the critical point (mm).

The blue zone indicates an important decrease in thickness, but because of its small size, it should not cause any issues neither to the production process nor to the piece performance once it is assembled.

With that analysed, it is time to understand how much effect has the elastic recovery on the final geometry.

After the 'springback' effect takes place and the punch is not in contact with the piece anymore, the results are the following ones:

- Von Mises stress distribution

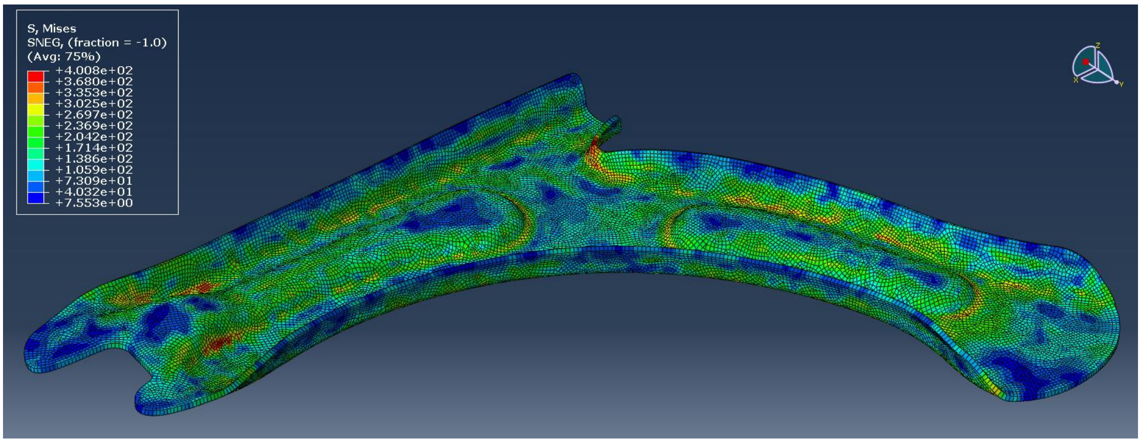

Figure 65: Von Mises stress distribution (MPa).

Regarding to the Von Mises stress distribution, it is easy to notice many changes, being the main one that the maximum value of stress has decreased to 400MPa. This is because a certain amount of stress was accumulated in the shape of elastic stress, which has been liberated once the punch has stopped exerting pressure onto the sheet metal.

- Maximum Principal Stress distribution

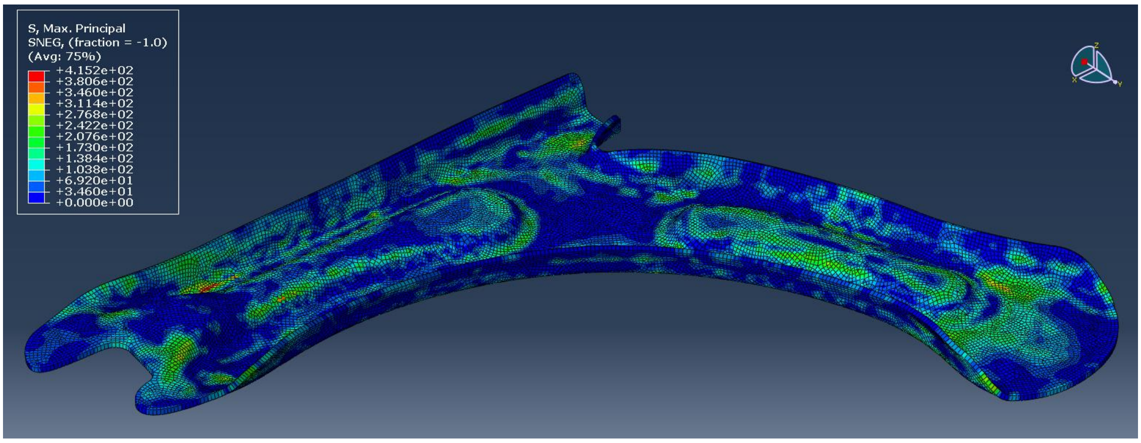

Figure 66: Max. Principal Stress distribution (MPa).

Because of the residual stress left on the piece, the Maximum Principal Stress variable shows a heterogeneous distribution, but as expected, this value has also decreased.

- Total displacement

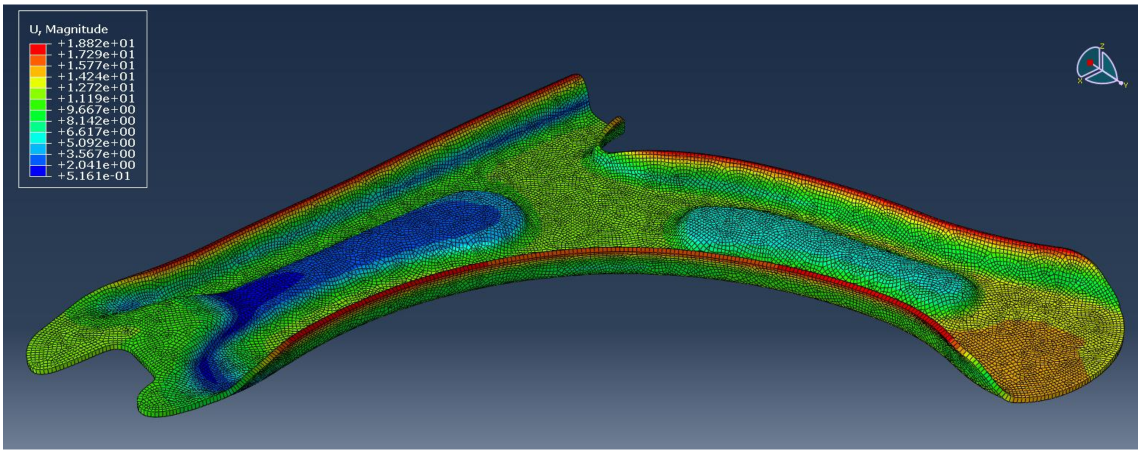

Figure 67: Total displacement (mm).

This is one of the most important distributions to understand the geometrical changes due to the spring-back. Comparing this distribution to the one before the elastic recovery, the main difference is that the transitions are slightly smoother, that is because the bend radius have increased and the bend angles have decreased. Though these changes are appreciable, it is believed that this will not prevent the piece from fulfilling its purpose.

- Vertical displacement

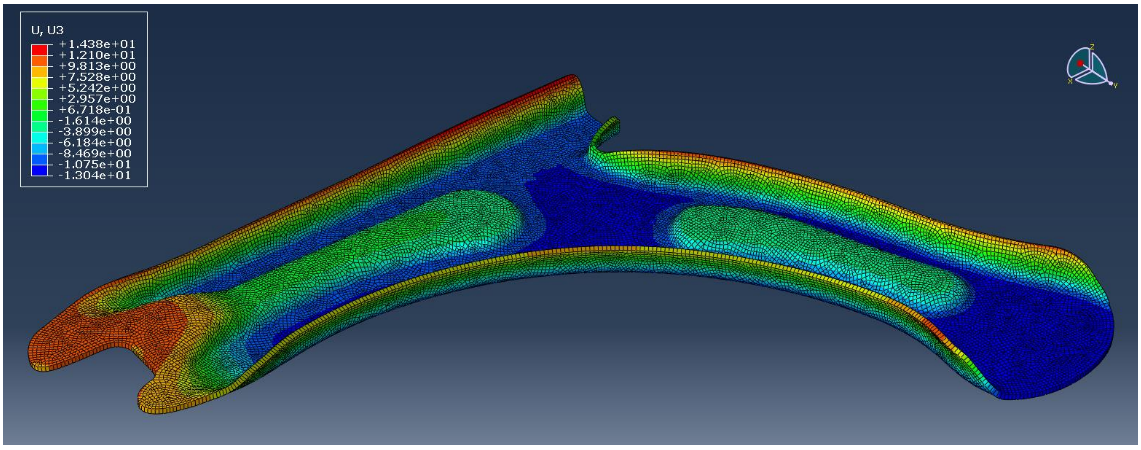

Figure 68: Vertical displacement after the elastic recovery (mm).

The vertical displacement distribution has changed considerably. That is because while liberating the sheet, the piece's walls exerted pressure on the die's walls, and as those are angled outwards, the entire piece rose almost 7mm, this effect can be seen in *Figure 68*, which shows a vertical displacement of -13mm compared to the -19,9mm before the 'springback' took place.

- Plastic strain equivalent

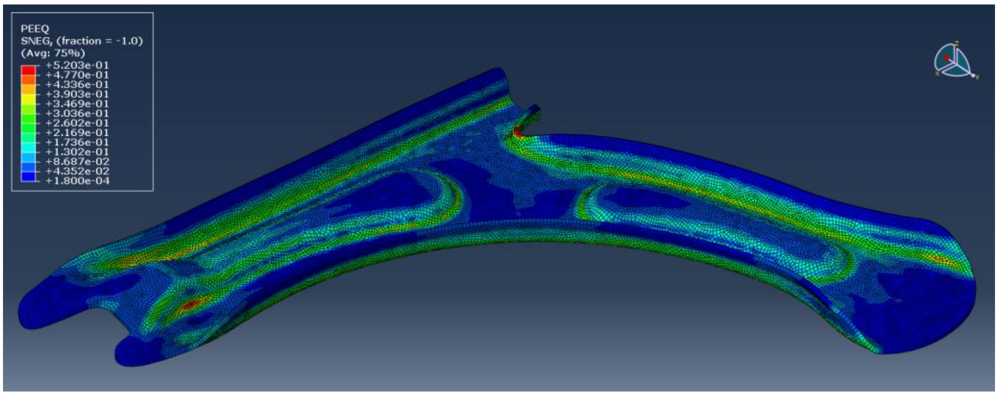

Figure 69: Plastic strain equivalent distribution.

- Thickness

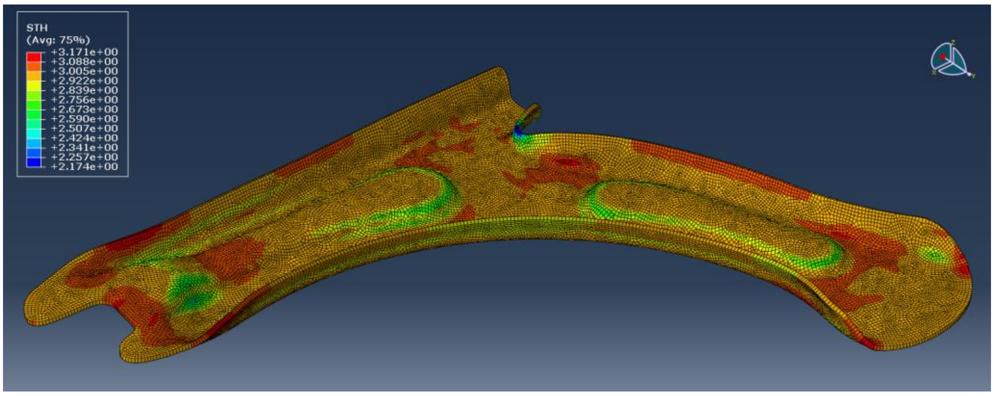

Figure 70: Thickness of the piece (mm).

Regarding the other variables such as the thickness or the plastic strain equivalent, no real differences can be noticed because of the elastic recovery, which is normal because there should not be any plastic deformation while this effect takes place.

7.4. OPTIMISED SIMULATION WITH FRACTURE CRITERIA

In order to ensure that the piece does not break at any state of tensions through the process, a simulation with failure criteria is set.

For that purpose, the FLD curve of the material is used, since this way, the software will be able to ensure that there is not any state of deformations that could cause the failure at any point of the sheet metal through the process.

The FLD curve shown below is the one which will be used for the simulation:

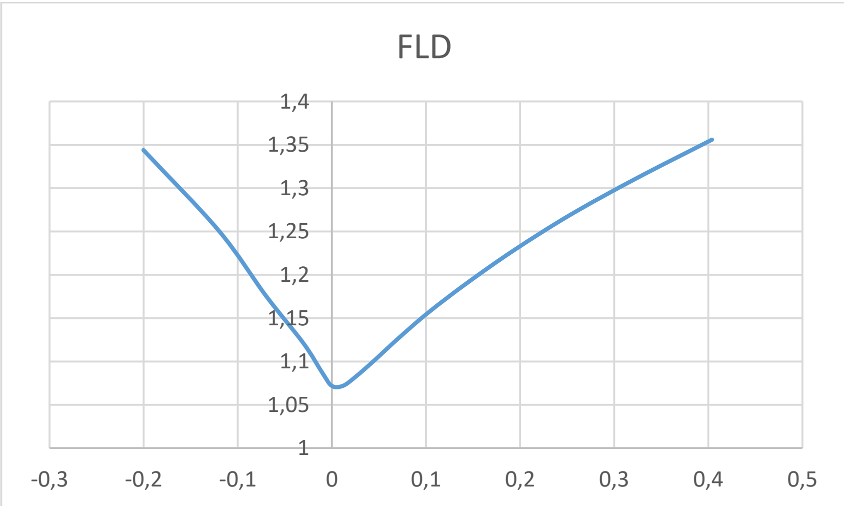

Figure 71: FLD curve of the sheet metal material.

After introducing the values of this curve in the software, the simulation provides the following results:

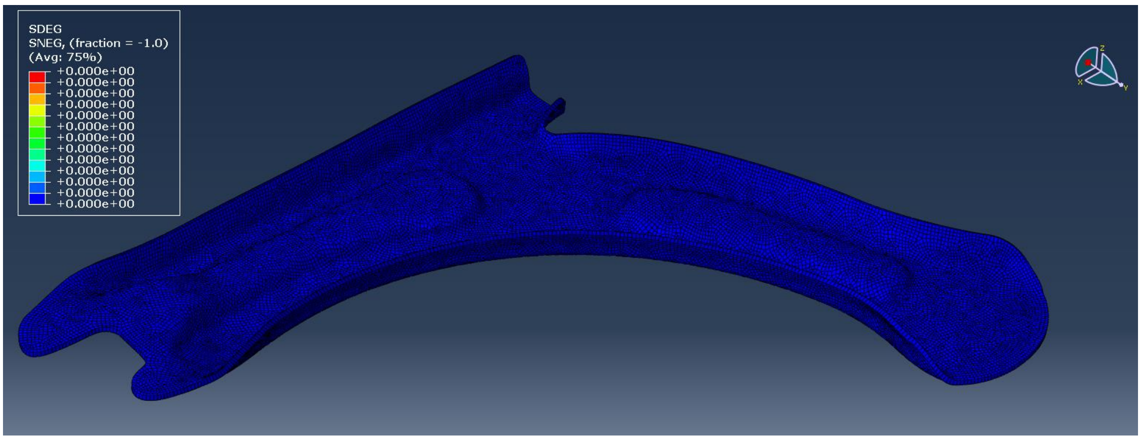

Figure 72: Damage variable distribution.

The variable SDEG shows the damage produced because of exceeding the values introduced in the FLD curve. This variable goes from 0, if there is no damage, up to 1 if there is.

As the results show, all the points of the piece are at a value of zero, therefore, there is no damage and the process can be executed without exceeding the ultimate limit state of the sheet metal.

8. DESIGN OF THE AUTOMATED PRODUCTION PROCESS

With the information obtained by the analysis of the simulation results, it is now possible to design the entire production process for manufacturing the control arm under study.

This production process has several stages, the lubrication, the blanking, the drawing and the finishes of the piece. Because of the type of piece that is being manufactured, the production will be for large series, so the process should be as automated as possible, allowing a high repeatability and decreasing the labour cost.

It is for this reason that the process is designed so it could operate without human intervention.

8.1. LUBRICATION STAGE

The sheet metal roll used should have at least a width of 554mm, the more adjusted the width is to that value the less scrap material will be produced on the blanking stage.

The sheet unrolls and is pushed forward with an automatic feeder, which can move the sheet at the desired speed and stop it when required. Thanks to this movement the sheet comes through the lubrication system, which in this case is the use of two automatic spray guns (*Figure 73*).

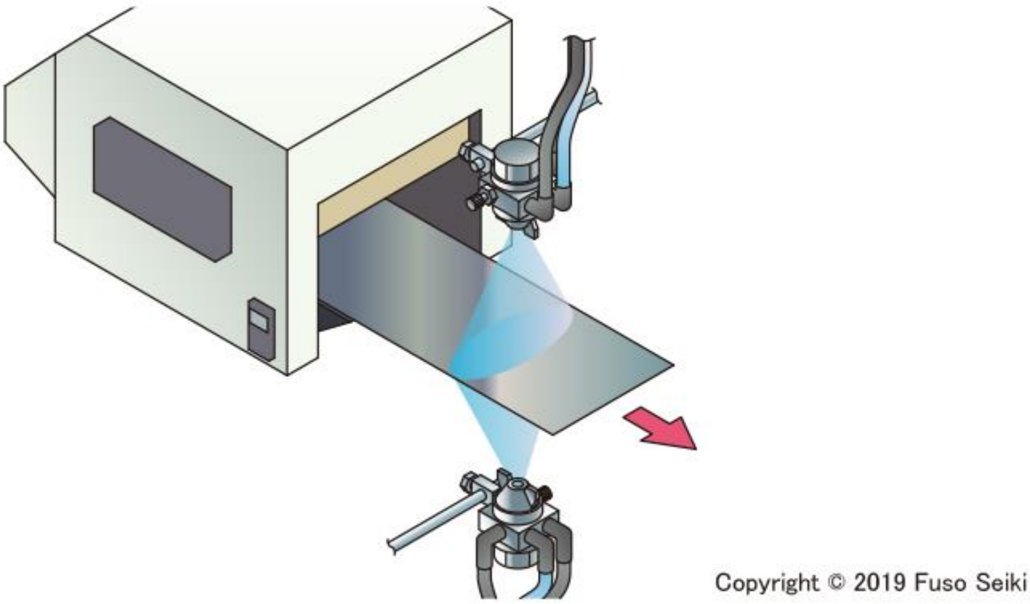

Figure 73: Spray lubrication system. [11].

This system allows an even lubrication on both sides and also has the advantage that there is no contact with the sheet's surface. On the contrary, the use of lubricated rollers, which is the most common system, does not apply the lubricant evenly in the reverse side of the sheet, since gravity makes it easy for the lubricant to gather at the bottom of the roller.

One disadvantage of the system selected is that if not controlled properly, there could be an overspray with the consequent contamination of the surroundings produced by the excessive amount of lubricant. Therefore, the guns should be positioned correctly, and the amount and pressure of lubricant released should be controlled to avoid that problem.

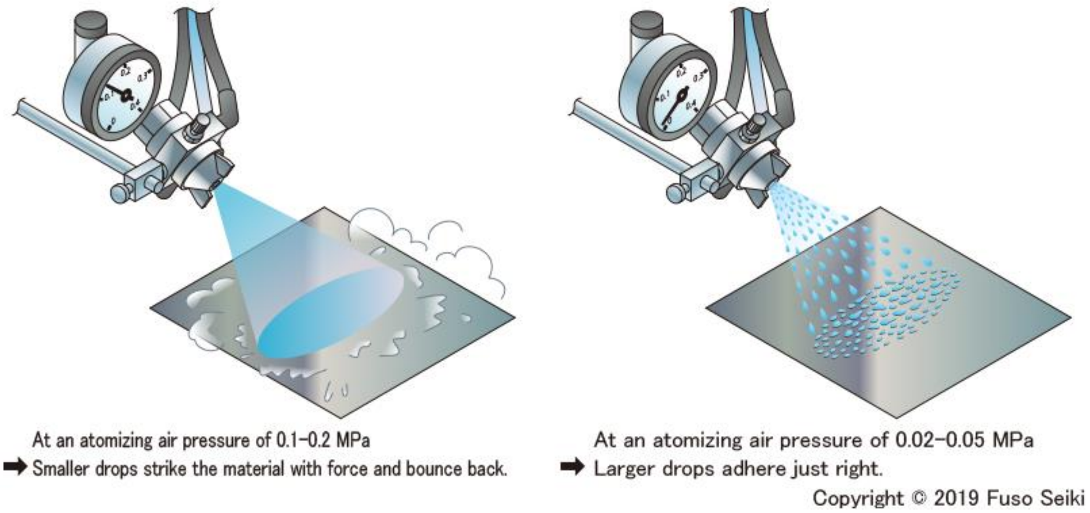

Figure 74: Effect of the pressure on the spray gun lubrication. [11].

8.2. BLANKING AND PUNCHING STAGE

The first operation that should be performed is the punching. The simulation shows no plastic strain in the zones where the piece has holes, so there is no problem in conducting the punching operation in the first place. However, once the holes are made, the sheet metal should be positioned with high precision to do the blanking, since changes on the positioning also change the spots where the holes should be in the control arm.

As explained in the previous section, the method used would be the implementation of an automatic feeder which pushes the sheet metal forward with a certain degree of precision. Nevertheless, if the sheet has to be positioned really fast there is another possibility, which is the use of an auxiliary punch which cuts the sheet in a way that when it moves forward it encounters a limit that does not allow the sheet to move forward anymore.

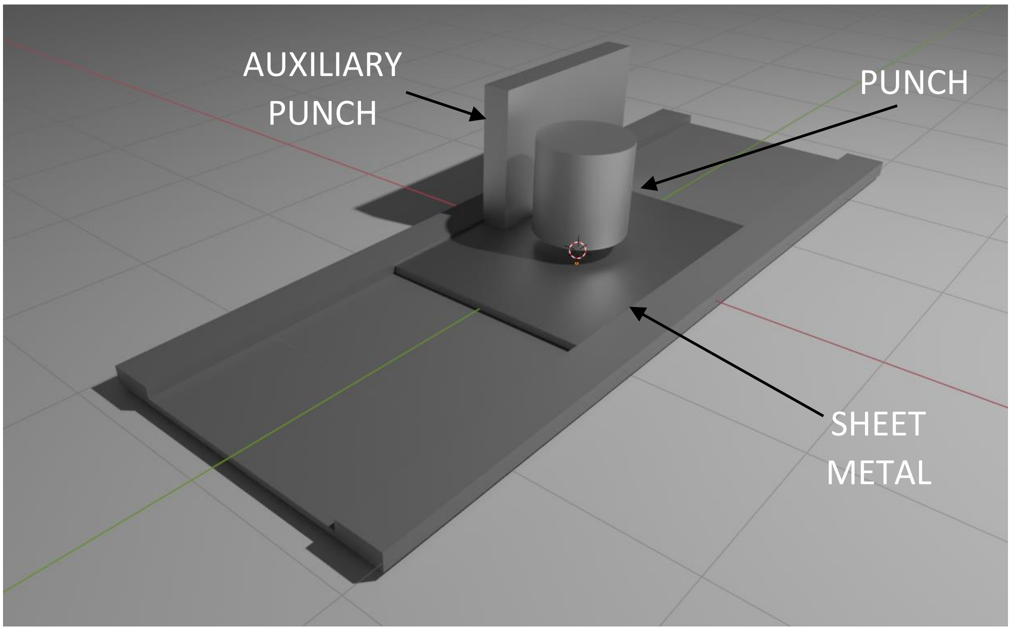

Figure 75: Auxiliary punch positioning system.

Figure 73 shows how this system works, with the rectangular auxiliary punch in one side of the sheet and the main punch in the middle. The obvious disadvantage of this system is that it produces huge amounts of scrap material and it needs of an auxiliary punch with its corresponding cost and maintenance.

After this stage, the blank should have the shape and position of the holes shown in *Figure 71*.

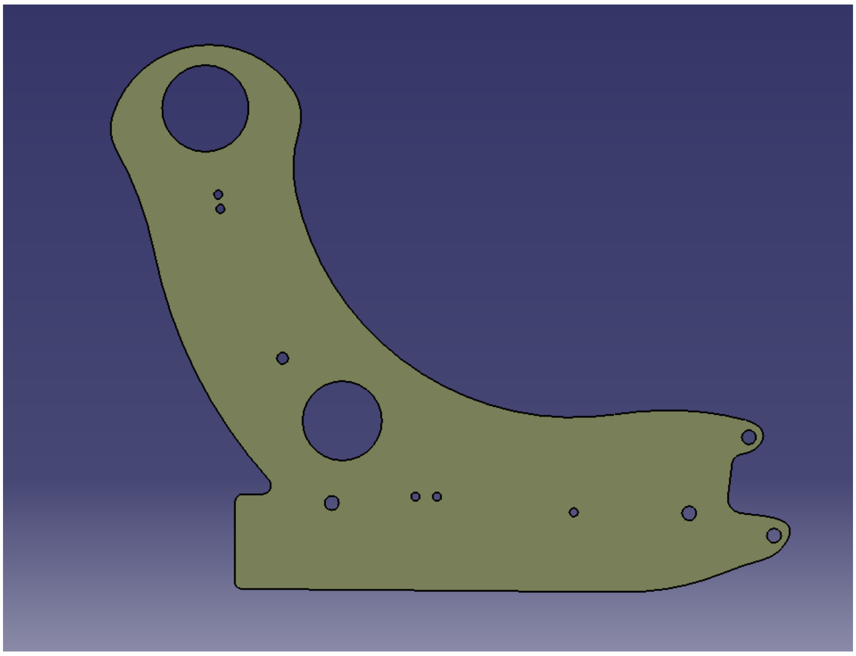

Figure 76: Blank shape before the drawing stage.

After this point, the material efficiency for an oblique disposal can be recalculated taking into account all the changes and the scrap material generated by the auxiliary punch.

8.3. DRAWING STAGE

This is the stage in which the drawing is conducted giving the control arm its shape.

Since the simulations show that the drawing operation can be performed in one phase, only a die, punch and holder is required, which can save time and decrease the cost of the process.

As explained in *Section 2.6.3*, many of the problems in this stage can be caused because of a bad design or maintenance of the tools. For this reason, the tools should be correctly aligned, the design should avoid buckling and the material of the tools should have enough surface hardness to avoid an early wear.

In this case, the simulations have been submitted with the tools set as discrete rigid, which allows to reduce the computation power since the software does not compute the deformation of the tools. However, for a complete analysis, a simulation that takes into account not only the tools' geometry but also their material should be launched and analyzed.

In this project, the deformations of the tools will not be simulated, but the initial geometry and material is given. The shape of the tools is the one used for the last simulation, with some bend radius increased and other general improvements mentioned in the analysis of the previous simulations.

About the tools' material, the choice is the steel DIN 1.2510 (100MnCrW4). This steel has the following chemical composition: 0,95%C, 0,20%Si, 1,10%Mn, 0,60%Cr, 0,10%V y 0,60%W.

It's mechanical properties, specially the hardness, make it one of the best choices for tools or anything that should stand high wear.

In order to obtain the desired hardness (between 62HRC and 64HRC), a quenching should be performed.

The recommended thermal treatment is the following:

The quenching should be performed from a temperature between 780 and 820ºC, and the tools should stay at this temperature till all their points are stabilized. After that, the tools can be introduced in an oil bath at 80ºC reducing the temperature of the tools rapidly and obtaining a martensitic structure. This gives the material a hardness of 64HRC, but also increases its fragility considerably.

For this reason, after this treatment, a tempering at a temperature between 100ºC and 200ºC is required. This will decrease the fragility of the tools and the hardness will stay between 62HRC and 64HRC depending on the tempering temperature.

9. CONCLUSIONS

The simulations have shown that at the beginning, with the first design of the tools, the drawing process would have failed in all likelihood. So after analysing the results, some improvements have been made and the final design of the tools allows performing the drawing operation in only one step.

For that reason, these simulations have saved the time and cost of trying in real life the operation without succeeding. Hence, that is proof that simulating this kind of processes is essential for any company trying to produce a new part.

Taking that into account, the material used for this simulation has been a steel with a high formability and a low elastic limit. The operation has been performed as cold forming, thanks to that, deforming the metal has increased the number of dislocations and therefore, the hardness and ultimate stress of the metal has increased as well.

However, if a higher strength steel is required, other solutions should be found, like performing the operation in several steps, or conducting a thermal treatment at the end of the process. Another solution could be to perform a hot stamping, that will allow higher deformations and will also produce a martensitic structure due to the phase change (while stamping, the temperature of the sheet metal reduced rapidly, generating this structure). The martensitic structure increases the hardness and tensile strength of the metal, but it is fragile, which means that a tempering should be conducted to obtain the end product with low fragility and high mechanical properties.

These solutions have an increased cost, because of the increased energy waste and the additional number of tools, in case of conducting the operation in several steps.

Because of that, the operation should be performed in one single step if possible, as it is in this project.

Furthermore, the results show large amounts of residual tension after the spring-back effect. This residual tension can be reduced by conducting a stress relief annealing. The benefits of this are reducing the risk of corrosion under stress, reducing the risk of cracks appearing on the piece and obtaining a better dimensional stability. On the contrary, this can reduce the higher mechanical properties obtained by cold forming, such as an increased hardness and ultimate strength.

Finally, the main purpose of the project has been achieved since the manufacturing process has been designed and the simulations shown that it is possible to manufacture the control arm as specified.

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11. ANNEXES

ANNEX A: FORCES NEEDED TO CUT A SHEET METAL

In order to get an approximation of the press capacity to make a certain cut, the following formula is used:

$$F_s = S_s \cdot \sigma_s \cdot k = p \cdot s \cdot \sigma_s \cdot k \quad \text{Equation 11}$$

The shear limit (σ_s) can be approximated as 0,7 times the tensile strength.

Where F_s is the shear force needed to cut the metal, σ_s is the shear limit, k is the safety factor and S_s is the section of the cut which can be written as the thickness (s) multiplied by the perimeter of the cut (p).

To be able to exert this force in a certain time, the press should have a certain power:

$$P_s = F_s \cdot \frac{c'}{t} = p \cdot s \cdot \sigma_s \cdot k \cdot \frac{c'}{t} \quad \text{Equation 12}$$

Where c' is the effective displacement of the punch which depends on the thickness of the sheet metal and t is the time required for the operation. c' is usually approximately $0{,}5 \cdot s$.

ANNEX B: FORCES NEEDED TO BEND A SHEET METAL

The expressions used to calculate the force depend on the type of bend that is being performed.

See *Section 2.4.4* to understand some of the types of bending operations.

$$F_{bend} = \frac{k_{fd} \cdot \sigma_T \cdot w \cdot s^2}{l} \quad \text{Equation 13}$$

Where k_{fd} is a constant that depends on the type of bending, for V shape it is 1,33, while for L shape it is 0,33 and for U shape it is 0,7. The σ_T is the tensile strength, w is the sheet's width, s is the thickness and l is the distance between supports as shown in *Figure 40*.

ANNEX C: FORCES NEEDED TO PERFORM A DRAWING OPERATION

It is important to know the force that the press should be able to exert on the sheet to deform it. This force should be lower that the shear force in order to avoid fractures and is given by:

$$F_{dr} = p \cdot e \cdot \sigma_s \cdot (\frac{D}{d} - 0{,}7) \quad \text{Equation 14}$$

That is the maximum drawing force applied onto the punch for drawing.

ANNEX D: CALCULUS OF THE DEVELOPMENT IN DRAWING AND DEEP DRAWING

The calculus of the development in drawing is essential before starting production. This can be done effectively in two ways:

- By calculating the dimensions manually using some simple relations
- By designing a blank with the approximate dimensions and simulating its deformation.

The first method could be easily used for simple shapes (like a disk). The second method, which is the one used in this project, can be performed for any shape, since after the simulation of the blank, the final shape can be analysed and then, the shape of the blank can be updated to meet the dimensions required in order to avoid having an excessive amount of scrap due to posterior cutting operations.

Though the second method is the one that is being used, in this section it is shown how to calculate the development for simple shapes by performing some easy calculations:

In this case, deep drawing should be differentiated from simple drawing.

- Drawing ($d/D < 0{,}56$)

  In this case, it is important to understand that the operation doesn't change the total volume of material that is being deformed.
  This means that depending on the final shape, it is possible to calculate the initial shape by matching the initial and final volume.
  Below one example is shown.

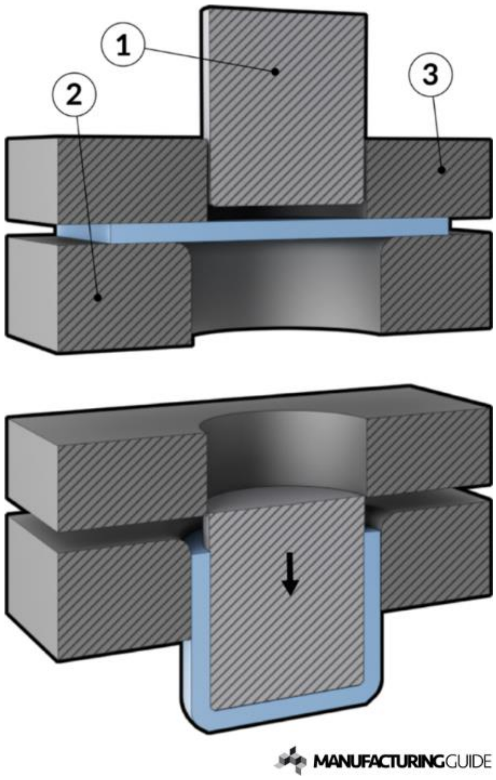

Figure 77: Example of drawing. [22].

$$V_i = V_f$$

$$\pi \cdot \frac{D^2}{4} \cdot s = \pi \cdot \frac{d^2}{4} \cdot s + \pi \cdot d \cdot h \cdot s$$

As the process of drawing should not change the thickness, the initial and final surface areas can be matched instead of the volumes (see that the thickness has no effect on the above equation).

$$D = \sqrt{d^2 + 4 \cdot d \cdot h} \quad \text{Equation 15}$$

This last equation gives the initial dimensions of the disk for performing this exact operation.

- Deep drawing (d/D ≥ 0,56)

In the deep drawing case, the theory is similar, but the process is different because it should be conducted in multiple steps to avoid the fracture of the piece.
In this case the factors k1 and k2 are defined. While k1 is the radio between the final and initial diameter of the first step, k2 is the same for all the successive steps following the first one. This factors are highly dependent on the material as shown in the following table:

Material	k_1	k_2
Cobre	0,50	0,75
Latón	0,52	0,75
Aluminio	0,55	0,80
Acero	0,56	0,75
Acero Inox.	0,60	0,80
Cinc	0,75	0,90

Figure 78: Ratios of change of diameter by material. [5].

Using these factors, it is easy to calculate all the diameters through the process, and the rest of the geometry can be calculated in the same way as simple drawing (by matching the initial surface with the final).