A mechanical power transmission: considerations about its manufacturability and life cycle

Luís Filipe Lopes de Araújo

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Orientador na FEUP: Prof. Luís Andrade Ferreira

Orientador na HAAS: Eng. Nuno Lopes

U.PORTO

FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

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Abstract

Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic science and mathematics and **engineering** sciences are applied to convert resources optimally to meet a stated objective.[3]

This usually means that design engineers are responsible for the creation of the initial draft of a new product, and thus should consider the next phases of product development (manufacturing and implementation) when designing a new product from scratch. If they are to consider those phases, then they should develop some familiarity with the subject, saving precious time and resources in the development of a product.

The main objective of this thesis was to develop the manufacturing of a pre-project developed earlier, creating a more robust and manufacturable product in the process.

To do that, it started with a full revision of the project, adapting the components to a predicted manufacturing process and introducing some revisions to the design when deemed necessary. After the revision was done, then detail drawings were produced for every component to be manufactured. At this point, codes were also developed for every component, to simplify the revision of the drawings.

After that stage, a more thorough analysis of the manufacturing processes used for each component was made, and some adjustments to the detail drawings were performed. Some specific drawings for certain manufacturing processes were developed, to communicate better the instructions to a possible manufacturer.

Also, manufacturing sheets, detailing the sequences of the manufacturing process and their parameter definition, were developed for each component. This required the selection of machines, tools and parameters for the chosen procedures. Those sheets serve also as a proof of the manufacturability of the proposed designs, and make it easy to budget the production.

Finally, this thesis ends with the thorough analysis of the machining of a component (a shaft cover), to explain better what needs to be done to fully develop a machined component.

Projeto de uma transmissão mecânica considerando a sua produção e o seu ciclo de vida

Resumo

Segundo a ABET, a Engenharia de Projeto é o processo de desenvolver um Sistema, componente ou processo para responder a necessidades identificadas. É um processo de tomada de decisão (muitas vezes iterativa), no qual as ciências básicas e a matemática, assim como as ciências de engenharia são aplicadas para converter recursos num produto capaz de responder ao objetivo proposto, de forma otimizada.[3]

O ramo de Engenharia de Projeto é, assim, responsável pelas primeiras fases de desenvolvimento de um produto. Isto significa que os engenheiros de projeto são responsáveis pela criação do produto, e para isso devem ter em mente as fases posteriores (de manufatura e implementação) quando formulam um novo produto. Para que os engenheiros de projeto tenham essas fases em mente, necessitam de desenvolver alguma familiaridade com essas temáticas. Essas preocupações podem levar à poupança de tempo e recursos no desenvolvimento de novos produtos.

O principal objetivo desta tese foi o de desenvolver uma possível solução de fabrico para um pré-projecto já desenvolvido, criando a partir deste um projeto mais robusto e fácil de fabricar.

Para isso, comecei por uma revisão completa do projeto escolhido, tentando adaptar à partida os componentes a um possível processo de fabrico e também introduzindo correções à solução inicial quando necessário. Após a revisão estar completa, foram criados desenhos de detalhe para todos os componentes. Nesta fase também desenvolvi uma codificação para os componentes, facilitando a compreensão dos desenhos.

Também desenvolvi folhas de fabrico, que detalham a ordem e alguns parâmetros dos processos de fabrico necessários, para cada componente. Nesta parte foi necessária já a escolha de máquinas, ferramentas e alguns parâmetros para os processos. Estas folhas servem também para atestar a capacidade de fabrico destes componentes, e facilitar a sua orçamentação.

Por fim, esta tese acaba com uma análise mais detalhada do processo de fabrico de uma peça maquinada (uma tampa de um dos veios), usando o mesmo para explicar as etapas necessárias para o desenvolvimento de uma peça maquinada.

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1 Introduction

Project engineering is the branch of mechanical engineering that develops a product from a phase where the product is nothing but a concept or an idea. The objective is to achieve a final design of a product that can be manufactured and function properly.

To do so, several steps have to be taken. First there needs to be an idea or concept to be developed, that idea then has to be studied, to see if it makes sense to develop it any further both in a economical and a engineering perspective. Basically the engineer must ask itself if the product can be done and if it makes economical sense to develop it. Only after that step can a preliminary design be developed, which in turn will be improved further until it can be manufactured [4].

In order to better understand this particular project, it is required to make a reference to a previous thesis, "Design and dimensioning of a test rig for efficiency measurements of wind turbine gearboxes up to 2.5 MW"[5], made by João Sousa under the guidance of Doctor Jorge Seabra. The reason for that reference is because this work is based on that previous work, and builds upon it in a way to improve it and take it a step closer to becoming reality.

That thesis developed an idea of a test rig that could measure the efficiency of a wind turbine multiplier gearbox. In in order to do that it would have to reduce the rotating speed of an electric motor to the one that a wind turbine usually spins. To make a high performing solution, after selecting several components, Sousa decided to design a reduction gearbox that could complement the solution he had developed.

He chose that component because it was the one that had the most parameters that could be tinkered with in order to optimize the solution. To better understand where that component fits in the design rig, we can use the following schematics in Figure 1, published by [5], in his thesis.

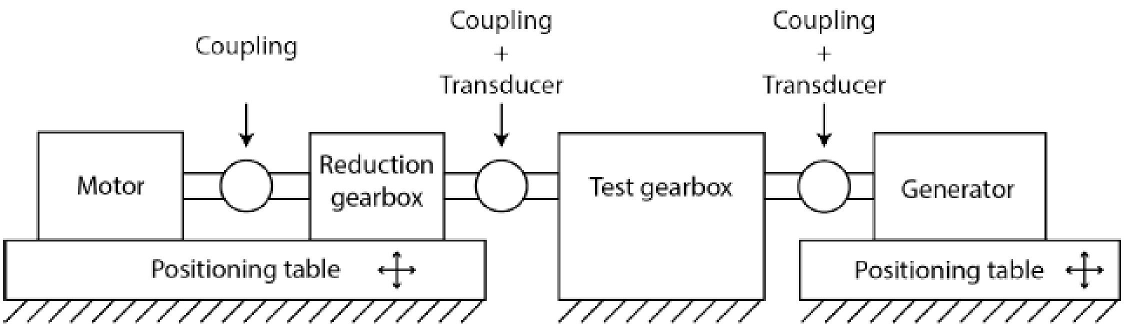


Figure 1 - Schematics for the multiplier test rig [5]

Now that some of the previous work is revised, a quick reference to the several phases of product development in engineering needs to be made (Figure 2):

Figure 2 - Diagram of the several phases of product development [4]

The work done previously by Sousa can be associated with the initial phases of concept development and market study, since that work has been completed, but also there was already an extensive work done on the preliminary design phase, that will be explored later when the intrincassies of this project are reviewed.

Finnaly, the work done on this thesis can be associated with the next steps towards the end of this product's development cycle, because it is included a part of design revision that is associated with the manufacturing process that was deemed appropriate for the component. Also, after the design and concept phases are over, the manufacturing and assembly processes will be studied and a solution sugested for this specific product.

1.1 Motivation

One of the definitions for Engineering found in the Webster Dictionary is “the application of science and mathematics by which the properties of matter and the sources of energy in nature are made useful to people” [6]. A good idea needs to be put into practice, and that’s where I believe this project is interesting, as it takes an excellent project and prepares it to be manufactured. It also benefits from the presence of an experienced partner, whom I will present in the next chapter.

I hope to learn a lot from this collaboration, since this project complements the theoretical knowledge I acquired during my 5 years course, with an approach from an industrial point of view.

1.2 HAAS factory Outlet

This thesis counts with the collaboration of an important partner, HAAS Factory Outlet. HAAS Factory Outlet is a subsidiary of the HAAS Automation group.

HAAS Automation Inc is the largest machine tool builder in the western world, manufacturing CNC vertical machining centers, horizontal machining centers, CNC lathes and rotary products. The company also produces some specialty machines [1].

Figure 3 - HAAS Automation Inc logo [1]

The company was founded in 1983 by Gene Haas, and the company’s goal is still to manufacture reliable and economical machine tools. Each and every machine is built to the exacting specifications of Gene Haas to deliver higher accuracy, repeatability, and durability [1].

HAAS Factory Outlet is a division of AfterSales S.A., being a distributor of HAAS machine tools for Portugal and Gallize, since 2004. To support the sales and maintenance departments, they have a fully equipped showroom, an extensive inventory of spare parts and qualified technicians and engineers to guarantee a quality service to their customers [7].

Another activity for this company is the development of manufacturing solutions for different industries. Besides providing the machine tool for the job, they also provide automated solutions and tools to optimize their clients manufacturing capabilities, including optimization of already existing manufacturing sequences.

For this specific project, there was collaboration between FEUP, with Eng. Luis Andrade Ferreira's support, and HAAS Factory Outlet, with Eng. Nuno Lopes being the supervisor at the company. The project counted with the expertise and experience of Eng. Nuno in manufacturing, to guide the project from a practical point of view and to ultimately create a link between Project Engineering and Manufacturing Engineering that makes the project interesting.

1.3 Objective

For this project, it was proposed to:

- Review a project developed previously by a colleague during their master's.
- Suggest alterations to the initial design (if applicable).
- Make a 3D design of the final solution
- Prepare technical drawings for every non-standard part and create specific manufacturing drawings when applicable
- Recommend a manufacturing procedure for each component, emphasizing the machining procedures
- Manufacture a prototype part using CAM programming on a HAAS CNC.

1.4 Method

During the development of this project was accorded to have regular meetings, both with Eng. Nuno Lopes and Eng. Luís Ferreira to review the state of the project and to discuss the proposed solutions. The meetings were arranged weekly so that I had time to implement the suggestions of my supervisors.

1.5 Structure

This thesis will be divided in 8 distinct chapters:

- **Chapter 1 – Introduction** – A brief introduction to the project, the motivation behind it and the way it was guided is presented.
- **Chapter 2 – State of the Art** – For this chapter a synthesis of some manufacturing processes that could be used to manufacture this product is made.
- **Chapter 3 – Eolic test rig reduction gearbox –** In this chapter it is presented briefly the project done by João Sousa that this work is based on.
- **Chapter 4 – New Solution –** This chapter is divided in two sub-chapters:
    - Design changes, that encompasses the alterations made in the first analysis of the project. These were not made having a specific manufacturing process in mind, but only suggestions to improve on the existing design.
    - Manufacturing design improvements, the changes exposed in this sub-chapter are intrinsically correlated to the manufacturing process chosen for that component/part.
- **Chapter 5 – Revision of manufacturing processes –** In this chapter are described some calculations and choices taken to give a better definition and justification of the manufacturing processes chosen for each part.

- **Chapter 6 – Technical drawings of equipment –** Some representative drawings are presented and their details are highlighted. Explications about the logic behind some divisions of drawings are also given in this chapter.
- **Chapter 7 – Machining and prototyping ETR01Co02 –** This chapter uses an example of the manufacturing of a relatively simple component, to illustrate the elaboration of a full machining plan for a component, highlighting the steps that need to be taken to achieve the desired results.
- **Chapter 8 – Conclusions and future work –** Some final remarks, and some suggestions of future modifications are presented.

2 State of the art

2.1 Conventional Machining

Machining is a manufacturing process that uses sharp tools and speed to remove material, metallic or polymeric generally, and to obtain the desired shape [8].

For this specific project, it is more relevant to define conventional machining (the one that constantly removes small chips during the cutting process) because that is going to be the primary process used to manufacture the different parts for the desired gearbox.

The chips are formed during the cutting process because of the intense plastic deformations generated. The tool later removes these. We can have a better understanding of this process using the Figure 4.

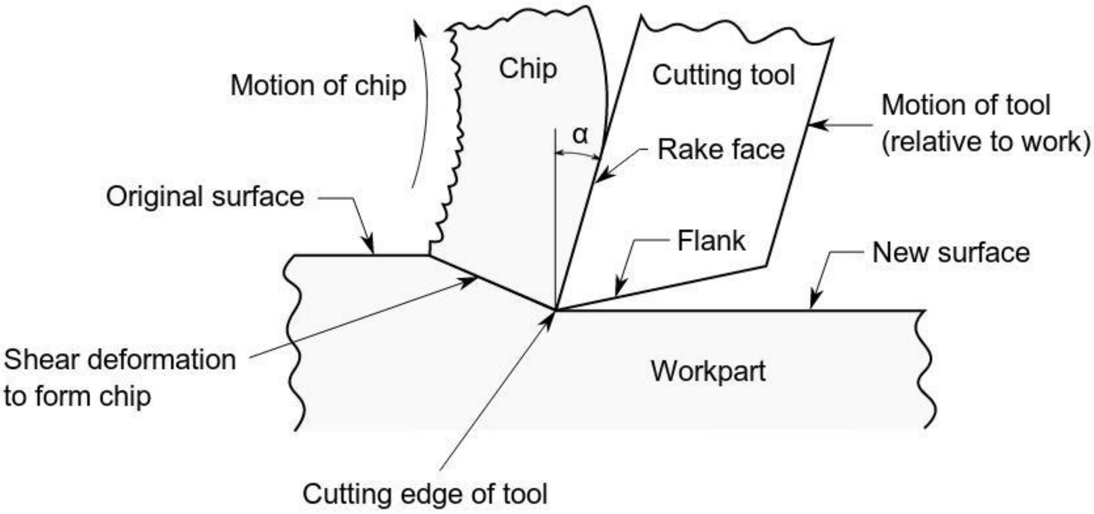


Figure 4 – Schematic representation of the process of chip forming and removing [9]

This process is only possible because the material has a component of plastic deformation before rupture, which allows the chip forming during machining. Because of that, the materials usually associated with this process are metals and polymers [10].

In a conventional machining operation, two distinct motions can be distinguished and studied, those are [11]:

- Primary motion, responsible for cutting (“Movimento de corte”, Portuguese).
- Feed motion, responsible for allowing more of the part to be machined (“Penetração” and “Movimento de avanço”, Portuguese).

On top of these two, we must also consider the depth of cut, that, together with the feed (speed at which the feed motion is set), and the cutting speed (speed associated with the primary motion), allows the operator to select how much material per cycle is cut, and determine the cutting conditions [12].

Two fundamental machining operations need to be distinguished, the Roughing cuts and the Finishing cuts. The Roughing cuts are higher productivity cuts that remove a lot of material to produce a shape close to the desired one. The Finishing cuts are more precise cuts that are used to achieve the desired surface roughness and tolerances on the workpiece. We can find that the first ones appear on the first stages of production and are characterized by higher cut depths, higher velocity feeds, but lower cutting speeds than their counterparts. The Finishing cuts, due to their low productivity are used as closely to the end of the production cycle as possible [12].

There are some fundamental machining processes that are different but similar in such a way that they can be grouped under this definition. Those are broaching, shaping, drilling, turning and milling. A brief exploration of each process will be given.

2.1.1 Broaching, Shaping and planning

Broaching, shaping and planning are the simplest of the different processes of machining. The basis of the process is quite simple and can be understood using the following figure.

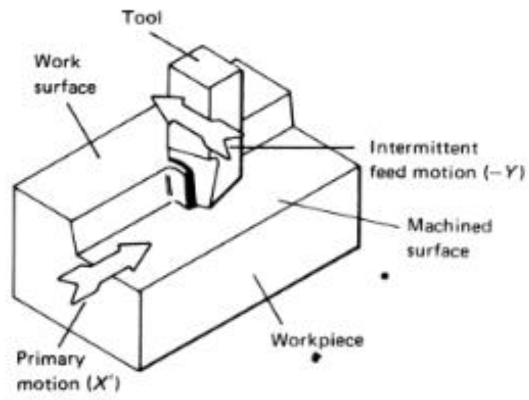


Figure 5 - Schematic representation of broaching and shaping machining processes [13]

Using the previous figure as basis, we can see that the primary motion (the one that generates the cutting) is linear, instead of rotational as with the other machining procedures that I will cover during this chapter.

The main difference between broaching and the other two, is the tool used. Usually the tool used both for shaping and planning is quite simple, having only one cutting edge, on a broaching machine on the other hand, the tool is a multiple tooth cutter, a comparison of both can be seen below in Figure 6 [14].

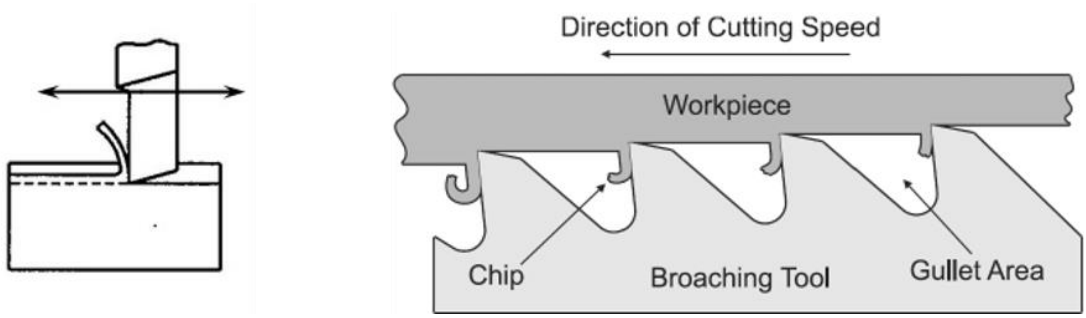


Figure 6 - Representation of: Right Shaping tool [15]; Left: Broaching tool [16]

Usually a broaching machine is more productive than its planning counterpart, because for each additional cutting edge of the broach, more material is removed during that movement, allowing it to compete with other high productivity machining processes, such as turning or milling [14]. Broaching machines can be, however, very expensive, only being justified for high productivity processes.

An additional difference must be established, this time between shaping and planning. Shaping is the process were the tool advances toward the workpiece, while planning is the opposite, the workpiece travels toward the tool. That intrinsic difference makes planning to be used on large workpieces (up to 15m of length), and shaping to be used on smaller ones, up to a 1x2m surface area [14].

2.1.2 Drilling

Drilling is the machining process used to obtain holes in workpieces. The holes are obtained using the rotation of a special tool, called a drill, whose edges allow for the removal of matter directly in front of the nose of the tool. The drill interacts vertically with the workpiece, so the deepness of the hole is only limited by the height of the drill. The cut material is then removed by being pushed back by the tool to allow the process to continue [8, 10].

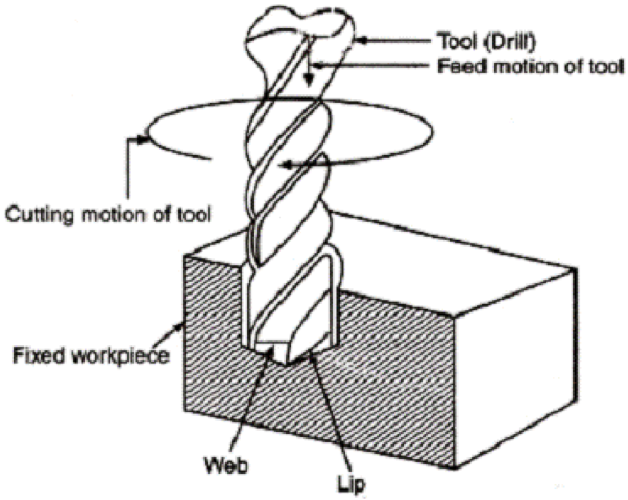


Figure 7 - Drilling process representation[17]

The primary motion on the drilling procedure can be identified as the rotational motion of the tool, because that is the one that effectively cuts the material, the feed motion is then the vertical movement, imposed by the quill on the tool [11].

This procedure can be done on multiple different machines, like a turning lathe, a machining center, or a purpose-built drilling machine. All of them have something in common though, that is that they need to be able to impose a relative rotation between the tool and the workpiece, and to be able to create the feed motion required. Having those requirements met, the machine can perform a drilling task.

The drill usually has a high length to diameter ratio, and thus should be used carefully to drill holes accurately, as they are somewhat flexible due to their length. The diameter of a hole produced by a certain drill is usually larger than the drill itself (oversizing), that can be attested by the fact that the drill is easily removed from the drilled hole. The oversizing depends on the drill, the drilled material and the drilling equipment, a better finished hole can be achieved using a reamer [14].

Figure 8 – Drill [18]

There are also several other operations that are similar to drilling, and require the same requirements as drilling, thus they can be done on similar machines. Those are:

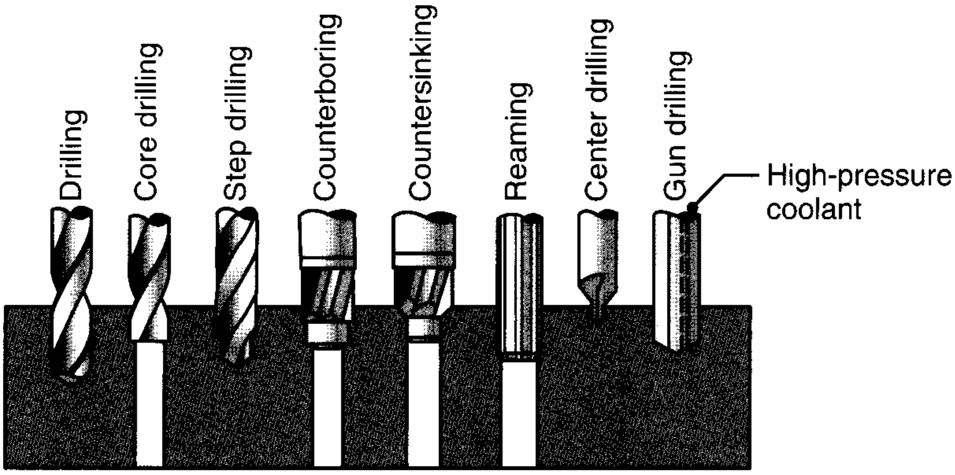


Figure 9 - Various operations, and tool, similar to drilling [14]

- Core drilling – Enlarging an already existing hole.
- Counter Boring – Creating cylindrical depressions to accommodate screw's heads
- Countersinking - Creating conical depressions to accommodate screw's heads
- Reaming – A drilling procedure to produce a better finished hole. Smaller tolerances and better surface roughness are expected in this procedure.
- Center/Spot Drilling – Short drilling procedure to either: allow the workpiece to be mounted between the headstock and the tailstock of a lathe (center drilling), start a hole in a desired location.
- Gun Drilling – Drilling deep holes with the assistance of purpose built tools and internal lubrication.
- Tapping – Procedure used to create internal taps on the workpiece.

For procedures like tapping, reaming and gun drilling, the classical configuration of a drill is not suitable to produce the desired results, so special tools needed to be developed for those. For tapping, the tool needs to be composed by multiple cutting teeth, as to diminish the pressure on the teeth during this procedure, and to provide a better overall result [14], a tapping tool can be seen bellow in Figure 10:

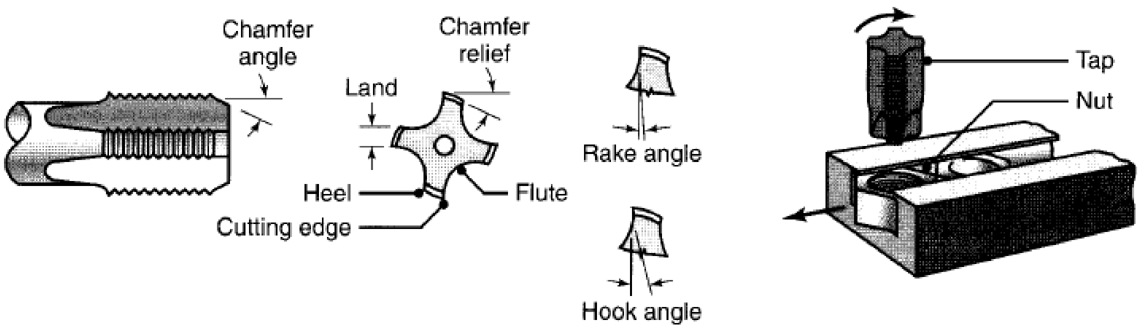


Figure 10 - Tapping tool specifics[14]

A reamer is a multiple-cutting-edge tool with straight or helical edges, that remove very little material, thus achieving a better finishing that its drilling counterparts [14].

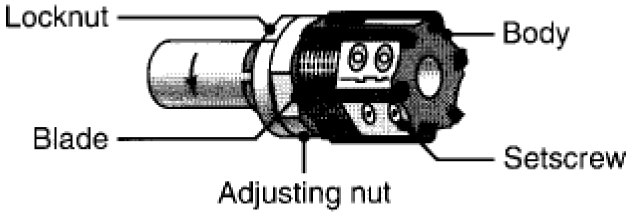


Figure 11 – Reammer [14]

Finally, the gun drill is a long drill that has an internal hole to force the cutting fluid through. This allows the gun drill to machine longer holes, with a good accuracy, and is also used to remove the chips. The gun drill does not need to be retracted to allow the removal of the chips [14].

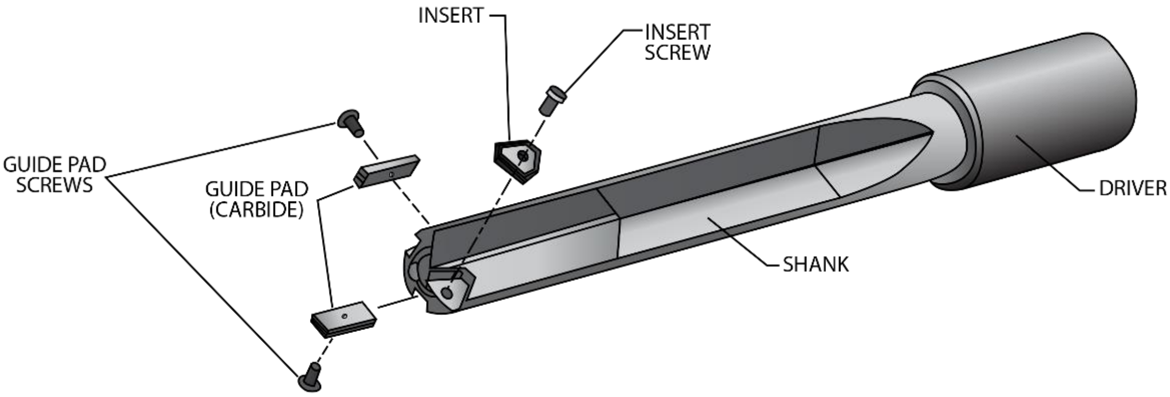


Figure 12 - Gun drill [19]

2.1.3 Turning

Turning is, by default, the operation used to obtain cylindrical and round shapes on the working piece. That's because the primary motion found in the turning procedure is the rotation of the workpiece itself, thus a round surface is easier to obtain.

Also, a feed motion is obtained when the tool is translated along the workpiece, both in the x (along the center axis of the workpiece) direction and the y (along the radial direction of the workpiece) direction[2]. An extra axis can sometimes be controlled, and that makes the turning machine able to create more complex geometries, which can sometimes be desired.

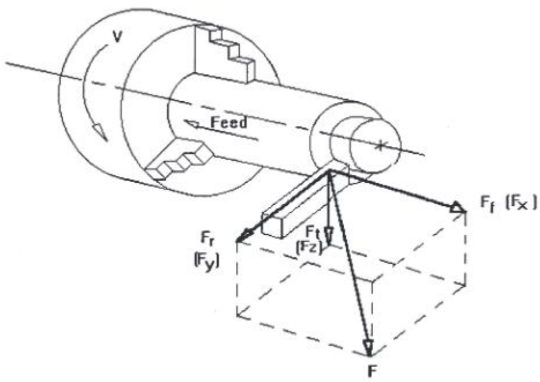


Figure 13 - Turning schematics and forces [2]

The tools designed for this machining procedure are relatively simple, when compared to others. There is, as with the others, special tools for each desired operation, but overall, they are usually single-edge tool, and can be single point or form tools, depending on what the operation requires [14].

Some operations and respective tools are shown below in Figure 14 [12]:

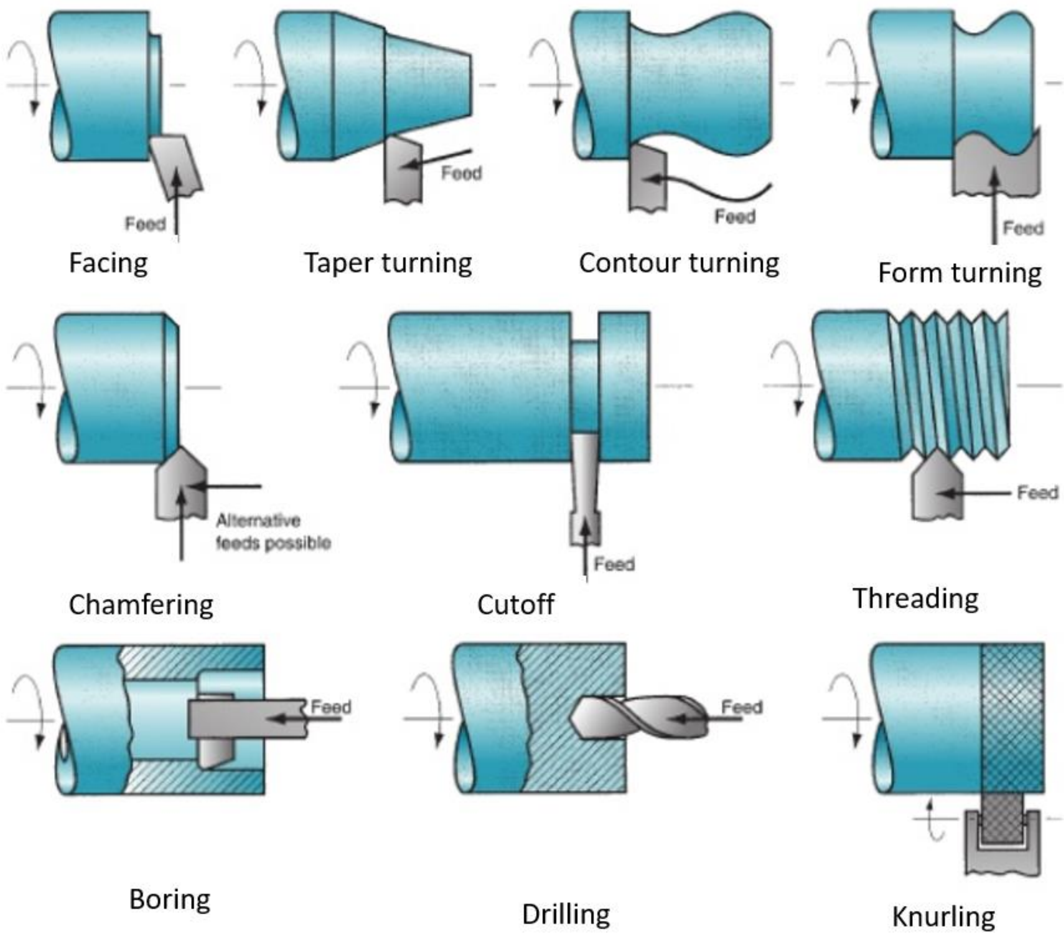


Figure 14 - Turning operations, modified [12]

- Facing: A radially fed operation that creates a flat surface at the end.
- Taper Turning: Creates a conical surface on the workpiece. Feeds both radially and longitudinally simultaneously.
- Contour turning: Creates a contour on the workpiece using a single point tool.
- Form turning: Uses a special form tool to create a contour.
- Chamfering: Creates a chamfer on the workpiece.
- Cutoff: The tool is fed radially into the workpiece to separate it in that specific point.
- Threading: Creates threads in the outside cylinder using a sharp single-point tool fed in an axial direction. This operation Requires a precise feed rate to create the threads, usually a larger feed rate than the other operations in order to skip some segments of the cylinder.
- Boring: A single point tool is fed to the workpiece internally, enlarging cylindrical holes in the workpiece
- Drilling: A drill is fed to the workpiece along its axis by the lathe.
- Knurling: Metal forming operation used to create a cross-hatched pattern on a cylindrical surface.

2.1.4 Milling

Milling is the most versatile of the before mentioned machining operations. It uses a rotating tool with multiple cutting edges, called a milling cutter, that is able to create multiple chips in one single rotation of the tool. The workpiece is fed to the rotating tool to be machined, usually resulting on a plane surface, although it is possible, by altering the path or the shape of the cutter, to obtain different shapes [11, 12, 14].

We can distinguish clearly two different kinds of milling, peripheral milling (left) and face milling (right), see Figure 15:

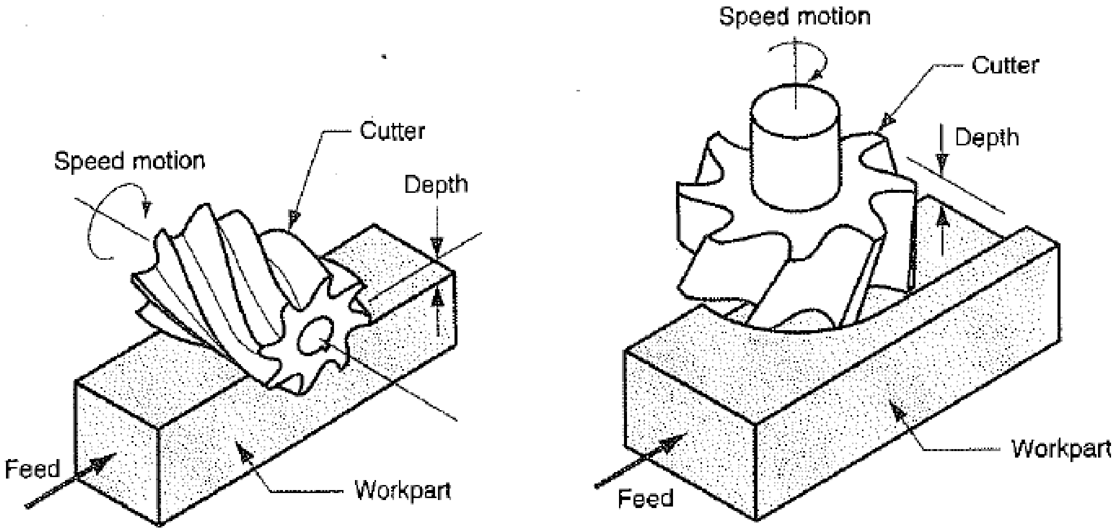


Figure 15 - Milling, two kinds of operation.[12]

Starting with face milling, in this one the mill's central axis is perpendicular to the workpiece, and it creates situations where the mill's diameter is bigger than the machined length (conventional face milling), where only part of the mill is used to machine the length, leaving the rest out of the workpiece length (partial face milling) and also a situation where the entire diameter is used to machine the piece, and the mill's diameter is smaller than the length to be machined (end milling). This kind of milling can also be used to machine slots, contours and complex surfaces due to its versatility [12].

For the peripheral milling, a big distinction needs to be made related to the feed direction of the workpiece. When the workpiece is fed in the opposite direction of the cutting teeth, it is called up-milling ("milling against the feed"), if, on the other hand, the workpiece is fed in the same direction of the cutting teeth, the process is called down-milling ("milling with the feed"). Down milling generates larger chips during the operation than its up-milling counterpart, but up-milling also has a tendency of lifting the workpiece from the worktable [12]. This will affect the kind of finishing that the face will have after the machining procedure is completed, but, since it is more economical and generates a better finish, down milling is usually the procedure used for peripheral milling.

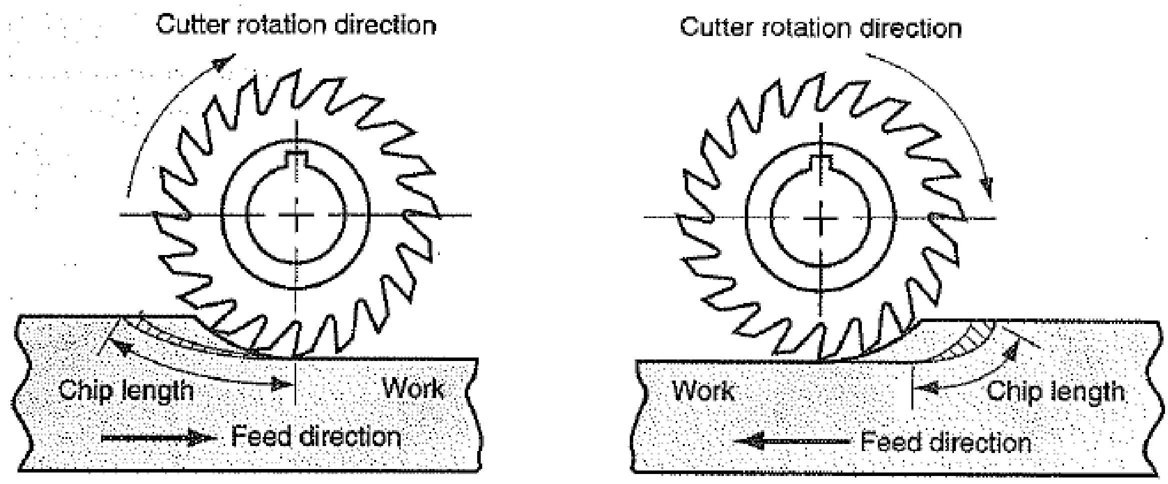


Figure 16 - Left: Up-milling; Right: Down-milling [12]

Comparing between peripheral and face milling, there are clear advantages in using face milling. Face milling can both generate better finished surfaces and be more productive than peripheral milling, so face milling should always be used when it is possible.

2.1.5 A point about machines-tools

Classically, milling machines, drilling machines and lathes, are manually operated machines, that allow the operator to control the cutting shape and the cutting parameters as desired. These machines depended heavily on the skill of the operator for the end results to be achieved, and it was also up to the operator to define how productive the machine would be. That made all the machining work very labor intensive, thus very expensive [20].

Figure 17 - Left: Drilling machine [21]; Center: Lathe[22]; Right: Milling Machine [23].

With the evolution of automation and computer science, it was inevitable that this labor-intensive job was to be gradually replaced by applying automation to these machines. These machines are now designated as a CNC (computer numeric control) machine [20].

A CNC machine can produce a lot more machined pieces than its traditional counterparts, but it is also a lot more expensive, so the investment should always take that into account. These machines require specialized workers, since there is now a component of CAM (Computer aided manufacturing) and CAD (computer aided design) that the operator needs to master before being able to command the machine properly, in addition to the already existing machining knowledge that they needed [20].

There are a few programs that are able to translate a CAD design to CAM programming, such as TopSolid, Autodesk Fusion or MasterCAM, that simplify the process a little bit, and even allow the operator to run some simple simulations before starting to manufacture the desired piece. CAM can also be programmed by hand, but since that is a labor-intensive process, it is usually only done as a last resource, or only to correct some mistakes that the program might have. [20]

There are two usual configurations for CNC machines, which are:

- CNC Machining Centers, machines that resemble a milling machine, but in this one the vertical movement is usually guaranteed by the spindle and the rest are guaranteed by the table. They can be characterized as horizontal or vertical machining centers (HMC or VMC) based on the spindle orientation [12]. These can also be supplied with a rotating positioning table, that allows the operator to rotate the piece using the machine [24].
- CNC Turning center, an automated lathe that can perform all the turning operations associated with a classical lathe [12]. Some turning centers (or CNC Lathes, as they are sometimes referred) also have the extra ability to rotate the tool (live tooling capabilities), and to control an extra axis, which makes them more versatile and expands their usual capabilities of only generating round surfaces [25].

Some general operations that can be performed on these “new” machines are [12]:

- Automatic tool changes, usually these machines have a tool drum capable of holding several tools at once and they can be commanded to change the tool automatically.
- Pallet Shutters/Automatic feeders, these are accessories that allow the machine to reduce the waiting time between pieces. The pallet shutters allow the operator to load the next piece and unload the previous one while the machine is cutting the current piece.
- Automatic workpiece positioning, allows the machine to position and rotate the workpiece independently, which in turn will lessen the time lost between machining positions.

Figure 18 - Left: CNC Mac. center HAAS DM-1; Right: CNC Lathe HAAS St-10 [26]

These machine, as they are more expensive to purchase and maintain and as they also need specialized operators to program and operate them, require a bigger volume of work to be done to justify their usage. In spite of being more expensive and requiring more time to set up, they are able to achieve better surface quality and tighter machining tolerances than their classical counterparts, thus being an important step in the evolution of the technology of machining [20].

2.2 Sheet metal bending

Sheet metal bending is one of the most common processes of sheet metal forming. Bending consists of informingly straining sheets of metal around a linear axis, that allows us to obtain some simple, but very common parts, in a cheap simple way [27].

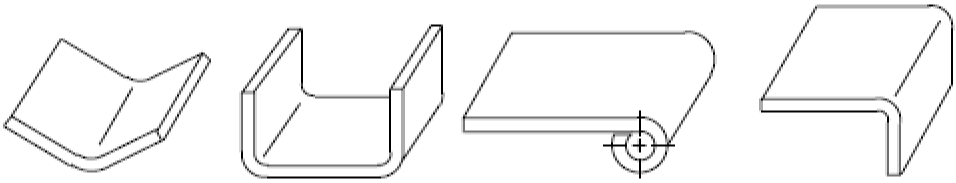


Figure 19 - Examples of parts obtained using sheet metal bending [27]

To explain the mechanics of this manufacturing process, some terminology must be explained, thus some attention to the following Figure 20 is required.

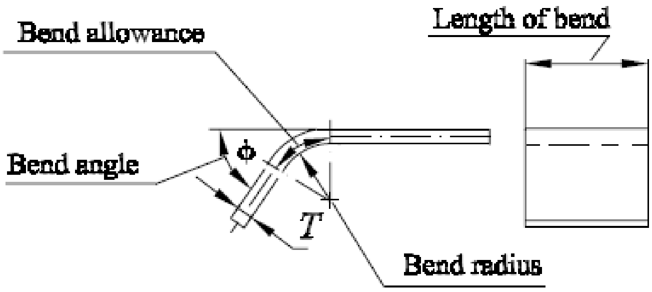


Figure 20 - Schematic illustration of the terminology used [27]

- Bend angle - ϕ – is the angle of the bent piece.
- Bend allowance – the arc of the neutral bend line.
- Length of bend – the length of the metal sheet.
- Bend radius – R_i - inner radius formed when bending.
- Bend allowance radius - R_n – radius in the bending neutral line

2.2.1 Sheet metal bending allowance

The first thing we need to know to manufacture a part by sheet metal bending is the bend allowance. Since the bend allowance is the section that suffers plastic deformation, it needs to be considered when choosing the appropriate sheet metal dimensions before bending.

When a large bend radius is considered, the neutral bending line (the line that doesn't suffer any strain from bending) is in the middle of the top and bottom of the sheet (mid-thickness) [27], and when that condition (usually represented by $R_i > 5T$) is guaranteed the bend allowance can be expressed as the length of the arc that has the radius of that line, or:

$$L_n = \frac{\pi\varphi}{180} R_n \tag{2.1}$$

If the bending allowance radius is exactly mid-thickness then the value would be equal to

$$R_n = R_i + 0.5T \tag{2.2}$$

But if a large bending radius is not considered, the neutral bending line is shifted towards the inner bend surface, thus instead of the 0.5 value considered for the large radii cases, a variable ξ, dependent on the sheet thickness and the inner radius, must be considered. So, the bending allowance radius would be:

$$R_n = R_i + \xi \cdot T \tag{2.3}$$

The following Table 1 contains values for this coefficient:

Table 1 - General values for the ξ coefficient [27]

Ri/T	0.1	0.2	0.3	0.4	0.5	0.8	10.	1.5	2.0	3.0	4.0	5.0	10.0
ξ	0.23	0.29	0.32	0.35	0.37	0.40	0.41	0.44	0.45	0.46	0.47	0.48	0.50

So, if we substitute the value of R_n in the original equation, we obtain:

$$L_n = \frac{\pi\varphi}{180}(\xi T + R_i) \tag{2.4}$$

That is going to be used to calculate the desired sheet metal length.

To choose the inner radius, two extreme values must be taken in consideration, the minimum bend radius (R_{min}), and the maximum bend radius (R_{max}). The minimum bend radius depends on the material ductility and is usually expressed by:

$$R_{min} = c \cdot T \tag{2.5}$$

Where c is a constant that is dependent on the metal that is going to be bent, and the state of the material (if it has been hardened or not), for a low carbon steel on a soft state the value is 0.5 [27].

The maximum bend radius is dependent on the maximum strain that the material can handle before rupture. So, a strain caused by the bending must be calculated first, and that is (e is the strain expected) [27]:

$$e = \frac{(R_i + T) - (R_i + T/2)}{R_i + T/2} = \frac{T/2}{R_i + T/2} \tag{2.6}$$

So, we can express the value R_{max} as being

$$R_{max} = \frac{T}{2e} = \frac{T \cdot E}{2 \cdot \sigma_{ced}} \tag{2.7}$$

If we choose a value of the inner radius between the two extreme values, no problem shall arise from this procedure.

2.2.2 Sheet metal bending force

Another aspect that needs to be considered is the bending force expected for the manufacturing of a specific part, since the equipment must also be chosen for the desired application.

We can expect that the inside metal fibers on the bend will be subjected to compression, while the outside fibers will be subjected to traction. These, in theory, should be equal in magnitude [27].

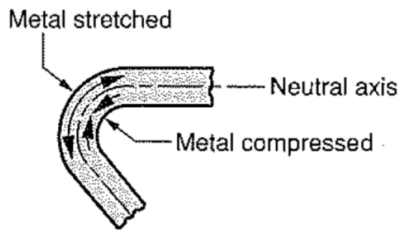


Figure 21 - Indication of strains in bending[12]

To be able to calculate the force required to bend the metal to the desired shape, we first need to know value of the moment of bending (M), that is just the sum of the moments necessary to create the compressed and stretched states of the metal in the bend. For this, we need to first define a coefficient called reduction radius, that will define if the moment of bending is in the purely plastic domain or the elastic-plastic domain [27]. This will be defined as:

$$R_r = \frac{R_n}{T} \tag{2.8}$$

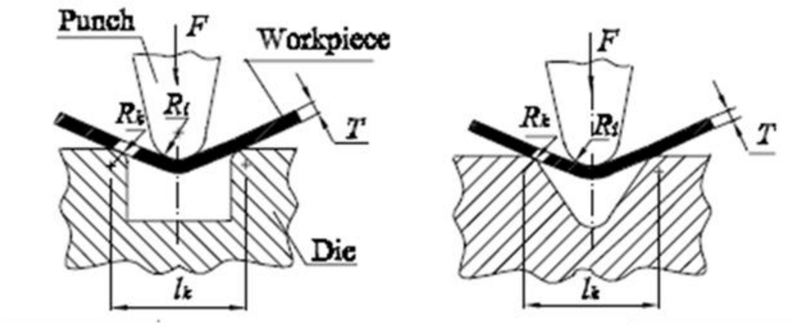
So, if the value of R_r is between the values of 5 and 200, the moment will be calculated as if it was in the elastic-plastic domain, but if the value of R_r drops below 5, then it should be calculated as if it was in the purely plastic domain [27]. The formulae for these are presented on Table 2:

Table 2 - Formulae for the calculation of the moment of bending

Elastic-Plastic domain	**Purely Plastic domain**
$\boldsymbol{M = \frac{\sigma_{ced} \cdot b \cdot T^2}{4}}$ (2.9)	$M = \frac{n \cdot \sigma_{max} \cdot b \cdot T^2}{4}$ (2.10)

Where n is a correction coefficient of hardening for the material (usual values between 1.6 and 1.8) and b is the width of the beam [27].

After the calculation of this variable, the bending force can be calculated for each specific situation, as an example it will be shown the equation to calculate a V die bending.



$$F = \frac{4M}{l_k - 2(R_k + R_t + T)\sin\frac{\varphi}{2}}\cos^2\frac{\varphi}{2}$$

Figure 22 - V die bending force calculation and representation [27] (2.11)

There are several other common situations explored in the bibliography that can be consulted.

2.3 Welding

Welding is a material joining process where the parts (two or more) are fused on their contacting surfaces, by the means of and application of heat and/or pressure. A first distinction must be made between welding, soldering and brazing, that being that in brazing and soldering only the added material is fused, while in welding the weldment's (parts to be joined) material is also fused, creating a junction with similar properties to the base material [12, 14]. The welding procedure depends on the way that the conditions of pressure and heat are created and the position of the parts to be joined together, so a few distinctions on those characteristics must be made to define the welding joint properly.

2.3.1 Welding processes

Welding processes can be distinguished then, by the way that the conditions of heat and pressure are created. Each distinct process has its advantages and disadvantages, so there is no "one-solution fits all" approach to welding, some processes are listed below in Table 3, according to the ISO 4063 designation [28]:

Table 3 - Reference numbers for some welding processes [29]

Welding method	Reference number
Metal-arc welding with coated electrode	111
Flux-cored wire metal-arc welding without gas shield	114
Submerged arc welding	12
MIG welding	131
MAG welding	135
MAG welding with flux-cored wire	136
TIG welding	14
Plasma arc welding	15
Oxy-fuel gas welding	311

The ISO 4063 standard encompasses a multitude of known welding processes, and designates them by a reference number, facilitating their identification and use [28]. Due to their common industrial usage, only three processes will be further explored in this review: Resistance welding, arc welding and oxy-fuel gas welding.

- **Resistance Welding**

When electrical current flows through an electrical resistance (like the junction of two metallic parts), heat is generated proportionally to the square of the electrical current applied. That is known as the Joule effect and is using that effect that resistance welding is possible.

Resistance welding is done by applying pressure to two metal pieces using copper electrodes, and, as seen in the figure below, an electrical current is then applied through those electrodes. Since the electrical resistance between the two sheet metal parts is greater than the electrical resistance between the electrode and the sheet metal, most of the heat is generated between the sheet metal parts. With the generated heat, the sheet-metal parts' temperature rises and the metal parts are welded together [12].

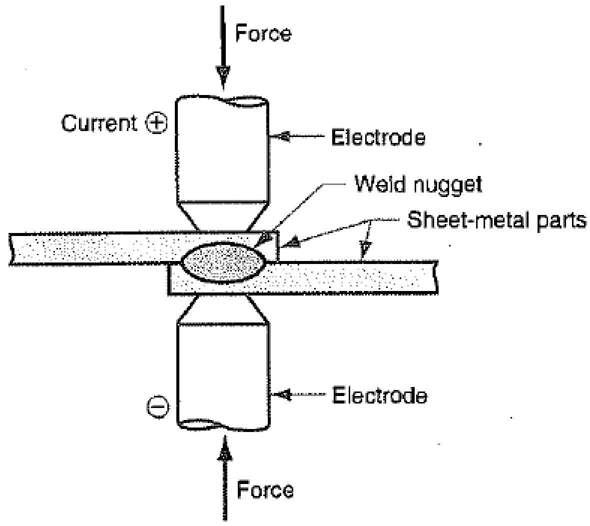


Figure 23 - Resistance Welding representation[12]

The successful application of this process depends of the heat generated and of the pressure applied. The electrodes must be able to endure the pressure and heat generated, and also have a low electrical resistivity, usually they are composed by copper to achieve those characteristics [12].

- **Arc Welding**

In this welding process, the needed heat is generated by an electric arc between the electrode and the workpiece. To initiate the arc, the electrode must contact the workpiece and then quickly be separated from it by a short distance, thus forming a pool of molten metal near the tip of the electrode. Filler metal is usually added to improve the resistance of the joint, though it is not always needed to accomplish a successful weld. The molten metal solidifies while the electrode moves along the joint [12]. A representation of this process can be seen below in Figure 24.

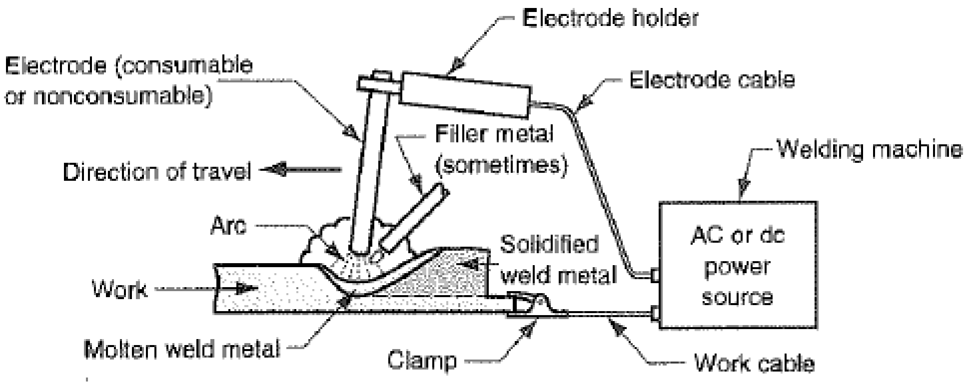


Figure 24 - Representation of arc welding [12].

We can better understand the process by analyzing the picture. Here we have the electrode, connected to an electrical power source, moving across the work (the junction to be welded) from the right to the left of the picture. On the tip of the electrode we can see the metal being fused to accomplish the weld and, as previously stated, the metal is solidifying on the wake of the electrode, represented by a darker tone in the figure. On a side note, to form an electric arc, the work must also be connected to the power source.

The movement of the electrode can be done by either a skilled worker (called a welder) or a machine. The problem of using manual labor in welding is that the quality of the weld is dependent on the worker's skill and work ethic [12].

The electrodes used in this process can be either consumable or non-consumable. If they are non-consumable, it is required that their melting point is much higher than the material they are welding, so, tungsten electrodes are usually the choice for these procedures. On the other hand, consumable electrodes should be similar to the material being welded, because they will compose the filler material added to the junction. If filler material is desired with a non-consumable electrode, it will have to be supplied by a separate wire, being fed to the molten metal pool [12].

Because of the negative reactions that some metals might have to the high temperatures achieved when exposed to the surrounding air, a protective air shield might be desired to achieve a quality weld. This will be called Arc Shielding and can be achieved by using a blanket of gas and/or a flux. The gas blanket can be either an active gas (oxygen or carbon dioxide) if the welded materials are ferrous, an inert gas (argon or helium), or a combination of both types, if that's desired. A flux is a substance that prevents the formation of contaminants in the deposited material, or dissolves them and allows them to be easily removed by the welder [12].

These two characteristics will be defining the designation that is given to the arc-welding process, ultimately, they also help to define the range of applications that a given arc-welding process has. As an example:

→GMAW- Gas Metal Arc Welding – is an arc welding process that has a gas blanket to shield the arc from the atmospheric air. It has the denomination of MIG (Metal Inert Gas) if the gas blanket is composed of only inert gas, or the denomination MAG (Metal Active Gas) if the gas is composed of active gas. 131 and 135 are their designations by the ISO standard [12].

→GTAW – Gas Tungsten Arc Welding – is an arc welding process that has a gas blanket, but the electrode is non-consumable and composed of tungsten. Has a common designation of TIG (Tungsten Inert Gas) and a designation of 14 by the ISO standard [12].

There are a lot of different processes in the subsection of arc welding. For additional information, a review of the ISO 4363 standard is recommended.

- **Oxy-fuel Welding**

For this welding process, the power source is not electrical power, like the resistance welding and the arc welding, instead a reaction of fuel and oxygen is used to produce the desired heat to perform the welding operation [12].

The most common fuel used is acetylene, when it reacts with oxygen it generates a high temperature flame that is directed by a torch to the welding joint. If filler material is desired, then a rod of material needs to be inserted manually [12].

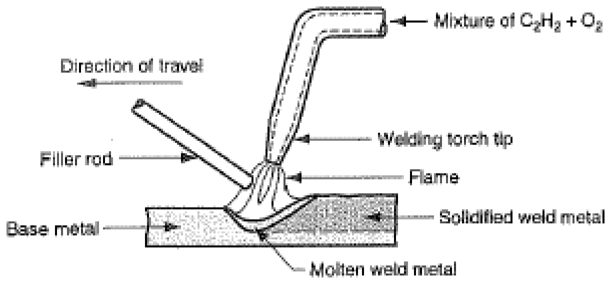


Figure 25 - Representation of Oxyacetylene Welding [12]

The reason behind the preference of acetylene among the different possible fuels, is that the flame generated by acetylene burn at a higher temperature (3480ºC) than his competitors.

This process can be hazardous for the welder if proper security guidelines are not followed, so caution is needed when using this procedure. It has the advantage of being portable and not needing electrical current to operate, thus being preferable when its versatility is necessary, like for example for onsite repair jobs [12].

2.3.2 Weld joints

The connection between the parts being welded is called a weld joint, and these can be classified by their geometry (Figure 26):

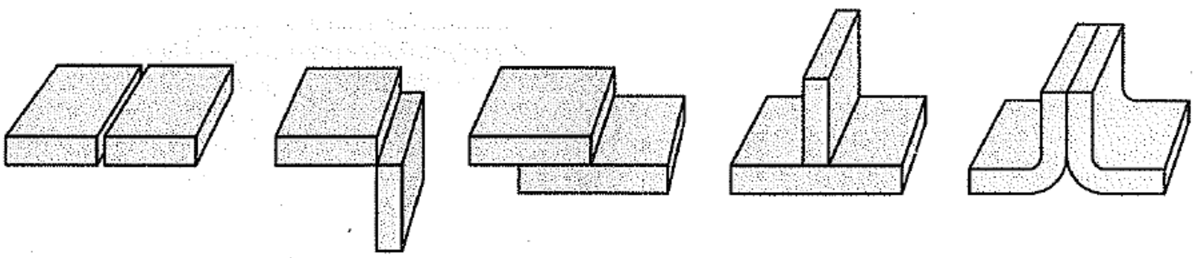


Figure 26 - Types of weld joints: Butt, Corner, Lap, Tee and Edge[12]

These are used define the types of welds that can be used to connect the parts in that position. The welds are the way that the parts will be welded together, while the joints describe only the relative position of the parts, so they describe better the junction created [12].

These joints might sometimes need special preparation to allow for the creation of a better welded junction. These are standardized by ISO 9692 [30], that should be consulted when projecting welding joints, this standard refers to the welding process used, the weld joint desired and the desired sheet metal thickness to be welded.

2.4 Thermal Cutting

Thermal cutting processes are manufacturing processes that generate heat to be able to remove material from a workpiece. The material is removed by elevating the temperature locally up to a point that, either by fusion or by vaporization, the material is removed. Usually these processes are associated with poor surface finishing, so subsequent processing might be required [12]. Three processes will be explored: laser cutting, plasma arc-cutting, oxyfuel cutting.

2.4.1 Oxyfuel cutting

These combine the heat generated by the combustion process with the exothermic reaction between the oxygen and the metal to remove material from the piece. The main cutting mechanism is the reaction between the metal and the oxygen, the heat generated in the region of cutting is used only as a support for the reaction [12].

This is only true for ferrous metals, for non-ferrous metals the main cutting mechanism is the heat generated, because they are both more chemically resistant to oxygen and have a lower melting point [12].

As it was for oxy-fuel welding, acetylene is the most used fuel for this process.

2.4.2 Plasma arc-cutting

In this process, plasma is used as a means to achieve temperatures high enough for the cutting process to be processed [14].

Plasma is defined as a superheated, electrically ionized gas, usually at temperatures around 10000-18000^{o}C, it is generated using an electric arc between the electrode inside the torch, and the anode (the work, part to be cut). In order to harness the heat energy of the plasma stream, a nozzle directs it to the work, melting the metal. The plasma stream them exits along with the removed metal through the kerf (see Figure 27) [12].

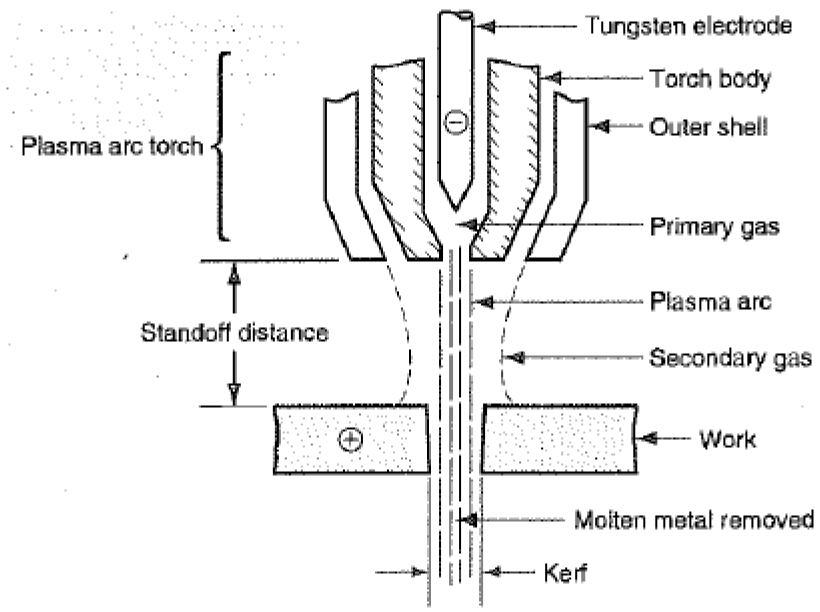


Figure 27 - Plasma cutting torch and cutting process [12]

The gases used for this process are nitrogen, argon and hydrogen, or a mix of those, these are designated as primary gases, since secondary gases or water can also be used to confine the plasma stream on the work. This process can be used on any type of metal desired [12].

2.4.3 Laser cutting

LASER stands for light amplification by stimulated emission of radiation, it is an optical transducer that converts eletrical energy into a laser light beam. A laser light beam is monochromatic and highly collimated (its rays are almost parallel to each other), characteristics that distinguishes them from regular light. These allow the laser beams to be focused onto a very small spot with high power density, thus justifying this application [12].

The only equipment required to generate and focus laser light beams are the Laser, to generate them, and conventional optical lenses, to focus the beams into a small point [12].

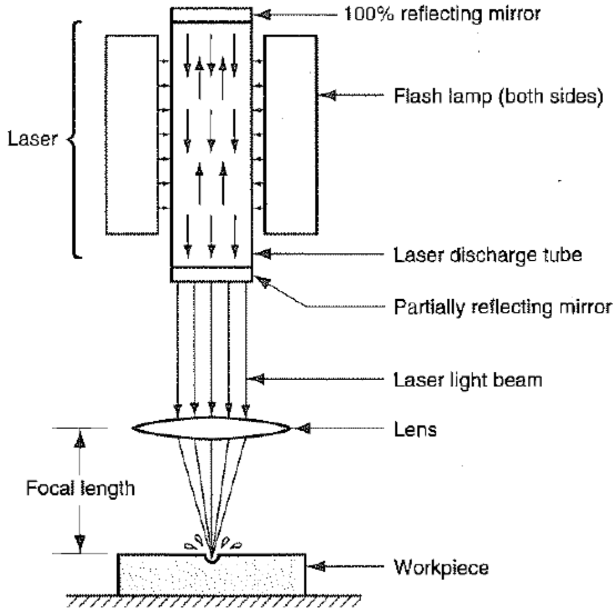


Figure 28 - Laser generation and focus for cutting [12]

Laser cutting as a technology has become a reliable alternative to mechanical cutting. It has the advantage of not needing special fixtures or jigs, and also because it doesn't need expensive tools and doesn't produce mechanical forces, that could damage thin work pieces. It has, among the other thermal cutting processes, special advantages like a high quality and smooth cut surface, small heat affected zone, a narrow kerf width, small deformation, square corners on cut edges, and no oxide layer [31].

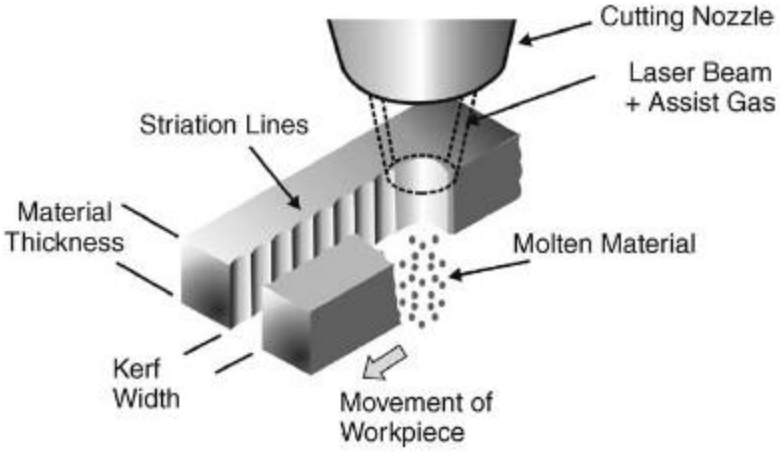


Figure 29 - Laser cutting process representation [31]

There are two main types of lasers currently used, carbon dioxide lasers, and Nd:YAG lasers.

- Carbon dioxide lasers have a higher efficiency, higher beam quality, higher depth of focus and a smaller beam diameter [31].
- Nd:YAG solid state lasers require less floor space, simpler maintenance, have easier beam alignment and they can cut materials having higher reflectivity than their CO_2 counterparts [31, 32].

There are almost no materials that can't be cut through laser cutting, but there are certain properties that determine the selection of the equipment. Parameters like the materials absorption to electromagnetic wavelength, thermal and electrical conductivity, melting temperature and surface condition. A careful selection is advised [31].

3 Eolic Test rig reduction gearbox

Due to environmental concerns, there has been a continuously growing investment in Eolic energy and other renewables. A Wind Turbine is a device developed solely for harnessing the power of the wind and converts it to electrical power.

Three main parts compose a typical wind turbine:

- The blades, which harness the power of the wind by resisting the flow of air, creating a rotational motion;
- The rotor shaft, which transmits the torque generated by the blades;
- The nacelle, which contains all the components necessary to convert mechanical movement into electricity.

The blades' generated rotational motion is a slow rotation, not suitable for power generation, so a gearbox should be attached to the rotor shaft to multiply the speed and make it suitable for power generation. Electricity generation needs to be produced at 60Hz (USA) or 50Hz (EU), meaning that the typical 4-pole generator needs a speed of 1800/1500 rpm to produce energy, so for 2.5MW wind turbines it is not unusual to find gearboxes which multiply the given speed by a factor of 100.

An Eolic turbine test rig should be able to measure the efficiency of the gearbox, because it is one of the most expensive parts in the wind turbine classical configuration, and also it needs to be optimized to improve its efficiency and reliability. Extensive research has been done to improve the design of these turbines, so it is important to support it by creating feasible and economical ways of simulating various scenarios that these gearboxes face. One test rig configuration suggested by Sousa [5] was based on already existing test rigs made by NREL (National Renewable Energy Laboratory), that can be easily explained by analyzing the diagram in Figure 30:

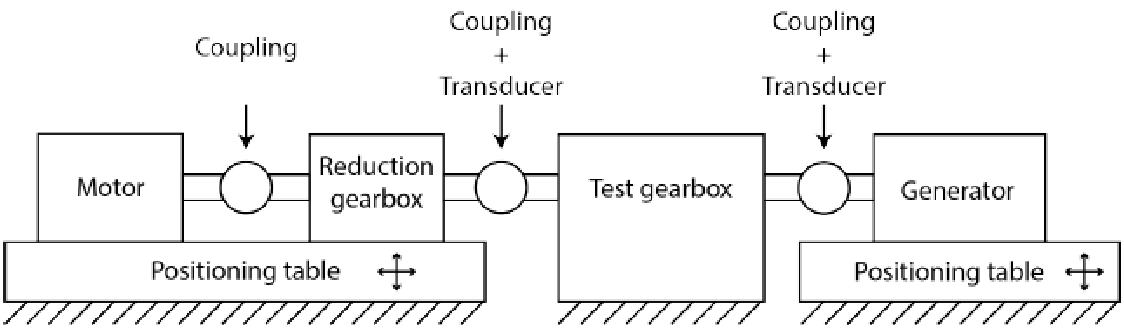


Figure 30 - Schematics for the wind turbine test rig [5]

The test rig would be driven by an electric motor, a Siemens H-compact 1LA4 636-4CN80, producing 2470 kW of power at a speed of 1495 rpm [33], coupled to a reduction gearbox that would reduce the input speed to a more appropriate rotational speed for a wind turbine, 15 rpm. The gearbox would then be linked to the gearbox that was going to be tested, and finally to a generator to recover part of the energy used during the procedure. Both positioning tables are used to allow the different gearboxes to be tested to be mounted easily with the rest of the test rig components.

After selecting a motor and a generator, the reduction gearbox must be developed to make the test rig a reality. For a reduction of 100 to be achieved, Sousa [5] chose to have two distinct gearboxes and divide the reduction between them. For the lower speed stage, a planetary gear train was chosen, since those are better prepared to deal with the high torque transmitted. For the first stage, a configuration using parallel helical gears has been chosen.

Since the parallel gear train is easier to adjust and optimize, that one was chosen for that purpose, in turn the planetary gearbox is going to be purchased from a manufacturer and was admitted that it would have a gear ratio of 7:1. With that in mind, the optimization of the parallel helical gears train can be done, admitting that the gearbox is going to be composed by two similar stages.

Sousa [5] has done a remarkable work in this aspect, he changed two variables to reach a better solution, gear arrangement and gear type.

On the gear arrangement, Sousa[5] compared solutions for single branch and double branch arrangements. The main difference is that in the double branch the power is divided by two intermediate branches, allowing for a 50/50 split of the torque transmitted through the gear train. Both arrangements can be distinguished in Figure 31.

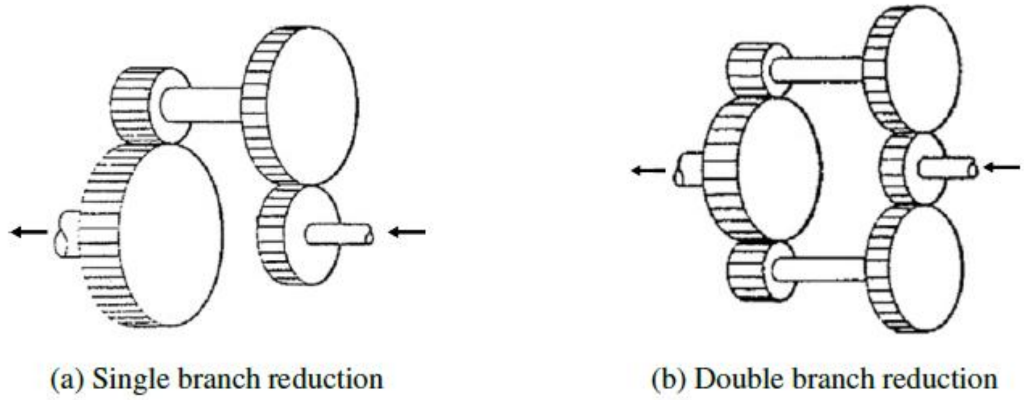


Figure 31 - Gear arrangements considered by Sousa [34]

As for the gear types, two were considered: single helical and double helical gears. Spur gears are not considered because of the noise generated and the lower load capacity. Since helical gears have a higher contact ratio, that solution should run smoothly.

The main advantage of the double helical gears is the absence of axial load on the shaft. Since the torque being transmitted through the gears is considerable, the axial component should be relevant, requiring sturdier roller bearings to withstand it. The load generated during the gearing in a helical gear is normal to a plane tangent to the teeth which, since it is not parallel to the shaft (like in the spur gears), creates an axial and a radial component. The double helical gears create symmetry in the middle that allows for a balancing of the axial component. That is achieved creating a left-handed helix and a right-handed helix that generate equal, but opposite, axial loads during gearing.

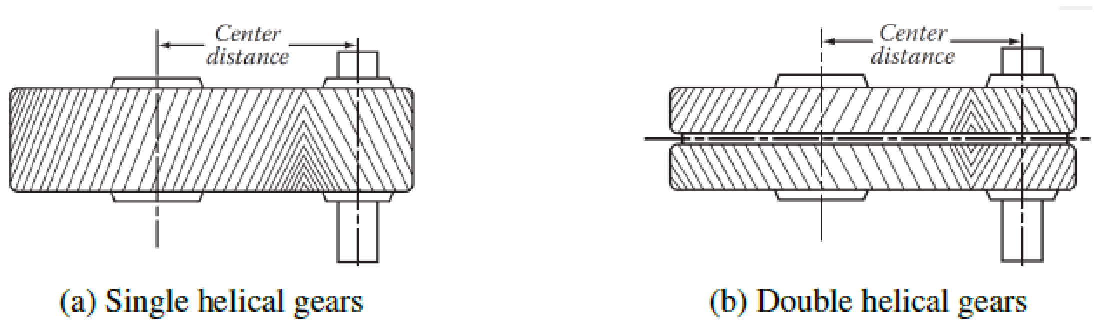


Figure 32 - Gear types considered by Sousa[34]

Sousa [5] created and compared solutions with different combinations of these parameters using KissSoft software. The conclusion he reached was that a configuration using double helical gears and double branch reduction gear arrangements, the final solution for the gear train was:

Table 4 - Final optimized solution calculated by Sousa

KISSsoft® cylindrical gear module input parameters regarding the optimized solution

Stage	1		2	
	Pinion	Gear	Pinion	Gear
m [mm]	5.5		8	
z	22	83	27	102
α [°]	20		20	
β [°]	15		15	
a [mm]	299.08		537.34	
b (gap) [mm]	140 (10)		210 (20)	
x* [mm]	0.242	-0.230	0.323	0.077
C_a [μm]	70		90	
h [mm]	4.77		7.09	

: Gear dimensioning results regarding the optimized solution

Stage		1		2	
		Pinion	Gear	Pinion	Gear
Operating pitch diameter [mm]		125.33	472.83	224.93	849.74
Mass [kg]		170		450	
Efficiency [%]		99.40		99.54	
Root safety		1.48	1.4	1.52	1.41
Flank safety		1.16	1.16	1.33	1.33
Scuffing safety	**Flash**	2.17		3.67	
	Integral	3.92		4.82	
Micropitting safety		2.37		2.58	
Contact Ratio	**Transverse**	1.57		1.56	
	Overlap	0.97		0.98	
Oil required [l/min]		23.47		18.03	

After this phase was finished and a solution for the gear train was found to be optimized, Sousa projected a possible design to allow the train to work and be positioned correctly. There were several components that he designed or selected that are:

- The **shafts** that support the gears and allow the input of torque and the correct output torque through the system. These were dimensioned using KISSys[1], using criteria of fatigue resistance for the final design developed. No shaft was allowed to have a safety factor of less than 1.2 or a maximum deflection of 0.2mm, Table 5 contains the final results achieved by Sousa.

[1] KISSys and KISSoft are design software for mechanical engineering calculations created by KISS SOFT AG, that can be used to calculate mechanical systems.

Table 5 - Final solution for the shaft dimensioning[5]

Shaft	Input	Inter right	Inter left	Output
Mass $[kg]$	40	94	84	240
Length $[mm]$	776.5	680	606	800
Max. deflection $[mm]$	0.192	0.227	0.154	0.199
Fatigue safety	1.47	1.20	1.83	1.22
Static safety	1.61	4.19	5.54	2.17

- The **bearings**, that allow for the free rotation of the shafts. Those were also dimensioned using KISSys Software, recurring to a method specified in the ISO/TS 16281[35] and ISO 281[36] standards. This method allows for the analysis of bearing life using factors such as shaft misalignment and tilting and oil contamination and filtration levels. The setting chosen was a contamination level of -/19/16 and $\beta_{40} = 75$, which resulted in the results of the following table.

Table 6 - Bearing life results [5]

Shaft	Model	Size $[mm]$	Life $[h]$	Losses $[W]$
Input	SKF *NU 318 ECP	90/190×43	36188	694
	SKF *NU 215 ECP	75/130×25	49615	251
Inter right	SKF *NU 2230 ECM	150/270×73	31639	568
	SKF *NU 2230 ECM	150/270×73	22784	582
	SKF 6230	150/270×45	28161	140
Inter left	SKF *NU 230 ECM	150/270×45	$\gg$100000	259
	SKF *NU 2230 ECM	150/270×73	32540	498
Output	SKF *NU 240 ECMA	200/360×58	43954	111
	SKF NU 2244 ECMA	220/400×108	44680	217

- The key joints, to connect the gears to the shafts. These components were also dimensioned using KISSys Software, the calculation method selected being the DIN 6892 B. The requisites were of a minimum safety factor of 1.2. The results are presented below in Table 7.

Table 7 - Key joint calculation results [5]

Shaft	Size[21] $[mm]$	Material	Quantity per gear	Stress $[MPa]$	Safety factor
Input	25 × 14 × 140	G12	1	622	1.24
Inter right	36 × 20 × 150	M7	1	476	1.2
Inter left	36 × 20 × 150	M7	1	476	1.2
Output	50 × 40 × 190	G12	2	622	1.24

- The housing, a welded container that supports the gears, shafts, bearings, and the auxiliary components. It also has the function of serving as a reservoir for the oil being injected for lubrication of the gears, and to allow the necessary maintenance to be done on the system. The cyclical and static loads supported are quite small, which makes those considerations less important than the consideration of being oil tight. This component will be composed by a base, a top cover, and smaller covers for inspection and to secure the shaft assemblies.

- The covers, a part of the housing as previously stated. Those are not loaded axially, so no formal considerations for the resistance of those components is stated. They are fixed using ISO 4017 M6 Hexagonal screws, except for the top covers, those are fixed using self-drilling screws because of the small thickness in the sheet steel on the top.

- The seals, to avoid oil leakage and external contamination. The shaft seals were selected using the shaft dimensions and the shaft surface speed. Results bellow in Table 8.

Table 8 - Selected shaft seals [5]

Model	**Size** $[mm]$	**Material**	**Sealing lip configuration**	**Max shaft surface speed** $[m/s]$
CRWH1	90x115x16	Nitrile rubber	SKF Wave	18
HMSA10	220x250x15	Nitrile rubber	Straight	14

- The retainer rings.
- The shaft spacers, to position the bearings and the gears.

For a thorough analysis of Sousa's solution, the original work [5] should be consulted.

4 New solution

During the first revision of the design suggested by Sousa [5], a few details were identified as possible changes to improve on the original solution. Some were replaced by more manufacturing-friendly solutions, or simply safer solutions that wouldn’t influence the final cost negatively.

A distinction has been made between design changes and manufacturing design improvements. The first category includes changes made to the chosen standard/bought components and changes made to the designed system. The second one includes design changes made to facilitate manufacturing and also some drawings made to aid the manufacturing procedure selected.

Each and every change made to the original design should be taken as suggestions and can and should be further enhanced.

4.1 Design changes

As previously stated this first category is meant to include changes made to the designed system and the chosen externally sourced components.

4.1.1. Substitution of the keys with splined shafts

Classically, the steel used for manufacturing shaft keys is the C3 Ramada (ANSI 1045). This steel, although not one of the most resistant one, is difficult to weld (especially under friction), which makes him the ideal candidate for the manufacturing of keys (the fit between the key and the shaft is suitable to create friction between the two).

Sousa [5], in his analysis, carefully predicted that the resistance of C3 would not be enough to endure the stress generated in the shaft-gear connections, so he chose a more resistant steel to counteract these limitations. This would theoretically work, but, because of concerns that the key might be welded to the shaft due to the friction generated, an alternative solution to the problem is supplied, splined shafts.

The major improvement of the splined shafts will be that the fit between the shaft and the gear will have tighter tolerances and thus will be less susceptible to the problem aforementioned. Straight-teeth splines are chosen because their manufacturing is simpler and because the improvements introduced by them should be enough.

To dimension the splines, two procedures were followed, one was selecting the desired teeth height, width and number of teeth that would be able to endure the torque transfer, the other was a confirmation that the alteration wouldn’t make the shafts less resistant to fatigue, since their safety factor was already low (1.2, according to Sousa [5]).

Starting with the torque transfer, ISO 14 [37] states limit values that should not be exceeded for the normalized straight teeth splines. This is not useful for this analysis since the standardized shaft diameters for splines only go up to 112mm, so a different method was required. The chosen method is given by INKOMA [38], a supplier of splined shafts. Three components resume the method:

- Calculation of the Torsional strain
- Calculation of the Torsional displacement
- Calculation of the Specific contact stress

These three components will then be compared with the material properties, and a minimum safety factor of 3 will be considered. The given equations are presented below:

Shaft:

Torsional strain $\tau = \frac{T_t \cdot 10^3}{W_p \cdot f_w} \leq \tau_{perm.}$

$W_p \approx 0{,}024 \cdot (d_2 + d_1)^3$

Torsional displacement $\vartheta = \frac{180°}{\pi} \cdot \frac{T_t \cdot 10^6}{G \cdot J_p}$

$J_p = 0{,}006 \cdot (d_2 + d_1)^4$

Hub:

Specific contact stress $p = \frac{T_t \cdot 2000}{h \cdot l \cdot n \cdot D_M \cdot 0{,}75} \leq p_{perm.}$

$h = 0{,}5 \cdot (d_2 - d_1)$

$D_M = 0{,}5 \cdot (d_2 + d_1)$

Figure 33 - Equations considered for the straight spline calculation[38]

Where,

- Tt is the Torsional Torque
- h is the spline height.
- b is the spline width
- l is the spline length
- d1 and d2 are the internal and external diameters
- G is the Shear Moduli

The results are presented on the tables below:

Table 9 - Spline calculation, input parameters

Gear	n (rpm)	Pot (W)	Shaft Diameter (mm)	Tt (Nm)
z1	1500	2500000	90	15915,5
z2	397,59	2500000	150	60044,9
z3	396,59	2500000	150	60196,3
z4	105,24	2500000	220	226845,7

Table 10 - Spline calculation, selected spline parameters

Gear	d1 (mm)	d2 (mm)	b (mm)	fw	h (mm)	l (mm)	n
z1	92	98	14	1	3	140	10
z2	156	162	14	1	3	140	18
z3	156	162	14	1	3	140	18
z4	222	228	14	1	3	210	24

Table 11 - Spline calculation, calculated values

Gear	Dm (mm)	Jp (mm4)	Wp (mm3)	Torsional Strain (Mpa)	Specific Contact Stress (Mpa)	Torsional Displacement (º/mm)
z1	95	7819260	164616	96,68	106,37	0,146
z2	159	61356380,3	771778,4	77,80	133,21	0,070
z3	159	61356380,3	771778,4	78,00	133,54	0,070
z4	225	246037500	2187000	103,72	177,81	0,066

Since all the values presented have a safety factor bigger than 3, the solution was accepted. As for the fatigue safety of the shafts, a direct comparison has been made between the concentration factors of both.

To obtain the concentration factor of the keyholes, the calculation sheets that Sousa [5] provided as annex, were consulted. For the concentration factors of the fillets (introduced because of the splines) Pilkey Peterson's [39] tables were consulted. Finally for the splines, it was suggested by Leen [40] on his analysis that a simple formula could be used to calculate the torsional concentration factor for the splines, that is:

$$K_t = 1 + \frac{1}{2}\sqrt{\frac{h}{r}} \tag{4.1}$$

Where h is the tooth height and r is the fillet radius of the splines (1mm radius was considered). In order to extrapolate the bending concentration factor, he suggested that a 25% increase was expected [40]. The calculations are presented below in Table 12:

Table 12 - Fatigue bending concentration factors comparison

Shaft nº	**Kfb - Key hole**	**Kft-Spline**	**Kfb-Spline**	**D/d**	**r/d**	**Kfb-fillet**	**Reduction (%)**
1	3,69	1,87	2,33	1,02	0,0111	1,4	36,79
2	3,06	1,87	2,33	1,04	0,0200	1,8	23,77
3	3,06	1,87	2,33	1,04	0,0200	1,8	23,77
4	6,57	1,87	2,33	1,01	0,0045	2,4	63,47

Since none of the concentration factors was bigger than the one originally given by the key hole, fatigue resistance is considered proven.

4.1.2. Substitution of the screws of the top covers

While analyzing the drawings, it was noticed that the component number 42 of the original drawing, the Emilie Maurin 62434 self-drilling screws that fix the top window covers to the housing, were made of A2 stainless steel [41].

As it is known, metals are susceptible to electrochemical corrosion if two metals with different electrochemical reactivity are in contact, it might corrode the more anodic (or less cathodic, less noble) of the pair. As a point of comparison, the galvanic series can be used to compare the two materials [42].

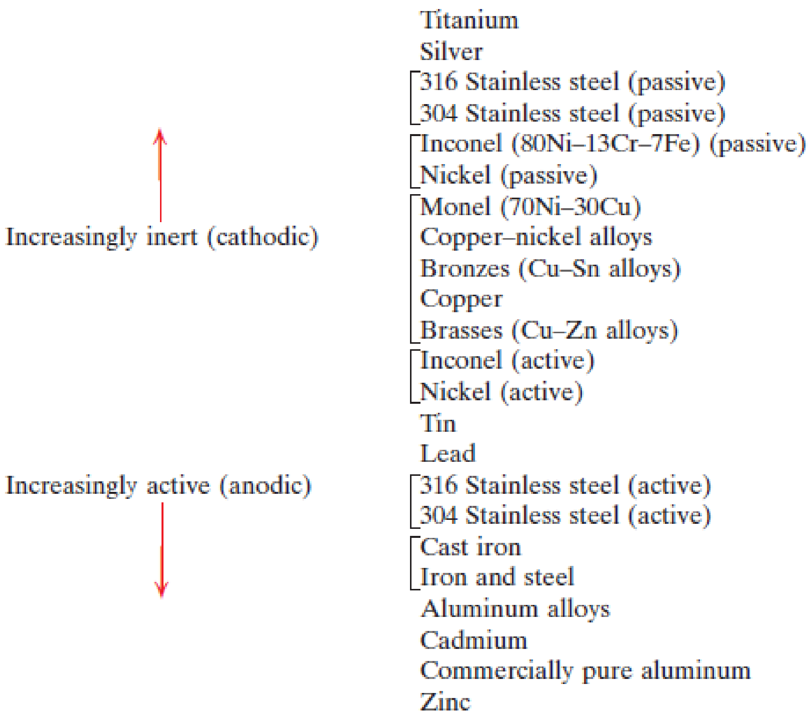


Figure 34 - The galvanic series (reduced) [42]

As we can see in Figure 34, steel is bellow stainless steel in the galvanic series, so it is not recommended for them to be contact materials, because it might originate problems in the housing material.

As an alternative, the cemented steel version of the same screw (code 33401) has been chosen, since it is Zinc plated, there should be no corrosion problems for the housing material.

4.1.3. Substitution of the screws in the shaft covers

This was a problem that would appear more on a practical point of view. The original screws selected for the side shaft covers were ISO M6 hexagonal screws, which were deemed too small.

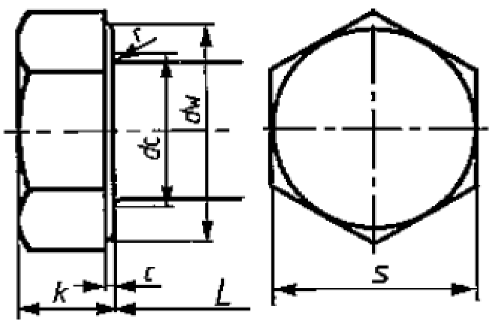


Figure 35 - Screw head dimension schematics

The value of the dimension “s” (that selects the tool to fasten the screw, see Figure 35) of the selected screws was only 10, since the 10mm wrench is relatively small for the average worker, a bigger screw should have been selected, if possible. There could also be some strain during the assembly that could damage the smaller screws, thus rendering them unusable.

The biggest screw that could fit the covers under the recent configuration was a M10 hexagonal screw, so that was the selected one.

4.1.4. Substitution of the plug

As for the plug, the selected ELESA TSD.40x1.5, it is made of techno polymer and, according to ELESA [43], it has a working temperature of 100ºC.

Although it is not foreseen that the continuous working temperature will be surpassed, due to the importance of the lubrication system, and due to the damages that an oil leak might cause, It is recommended the substitution of the plug with the ELESA GN 742-50-M40x1.5-OS-1. This plug has the same geometry of the first one, but it is made of aluminum and its working temperature is 180ºC, giving us a comfortable safety against rising temperatures [44].

Although it is expected that the plug might have a higher purchase price than the first one, it shouldn’t be relevant on the overall product price.

4.2 Manufacturing design improvements

These improvements were made to facilitate the manufacturing process of the various parts that compose this transmission; no relevant alteration to the gear train was made on this chapter.

4.2.1 Housing

The housing can be seen as multiple 20mm thick steel sheets welded together as to assemble a box, capable of withstanding the forces generated during the operation of the transmission and to hold the lubricant (to allow the lubrication system to perform its tasks).

Two cheaper manufacturing processes were selected to produce the housing, sheet metal bending and welding. Those manufacturing processes were chosen because they are simpler and more versatile than for example metal sheet forming, and require a lesser initial investment on both machines and tools.

Since it was not possible to produce the housing through those two manufacturing processes, some alterations to the original design were needed. The reason behind its impossibility was that the central sheet could not be bent if its height was bigger than half of its width, it would be physically impossible because of the needed tool clearance needed to bend the sheet.

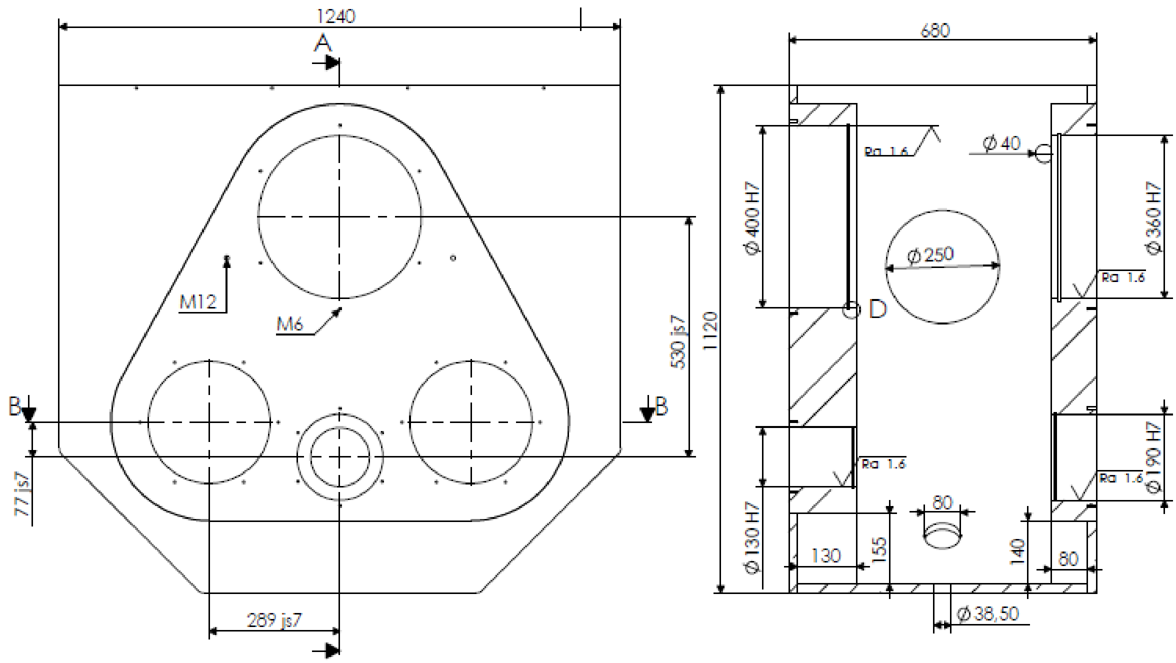


Figure 36 - Early housing design by Sousa[5]

As we can see in Figure 36, 1120mm is more than 620mm, which is half of its width, so we cannot bend the metal sheet to its position in this design.

The suggested alteration is to divide the central wall is half, and then weld the two parts together, but to do that we need to move the drain plug away from the center of the wall. The proposed design ended up like this:

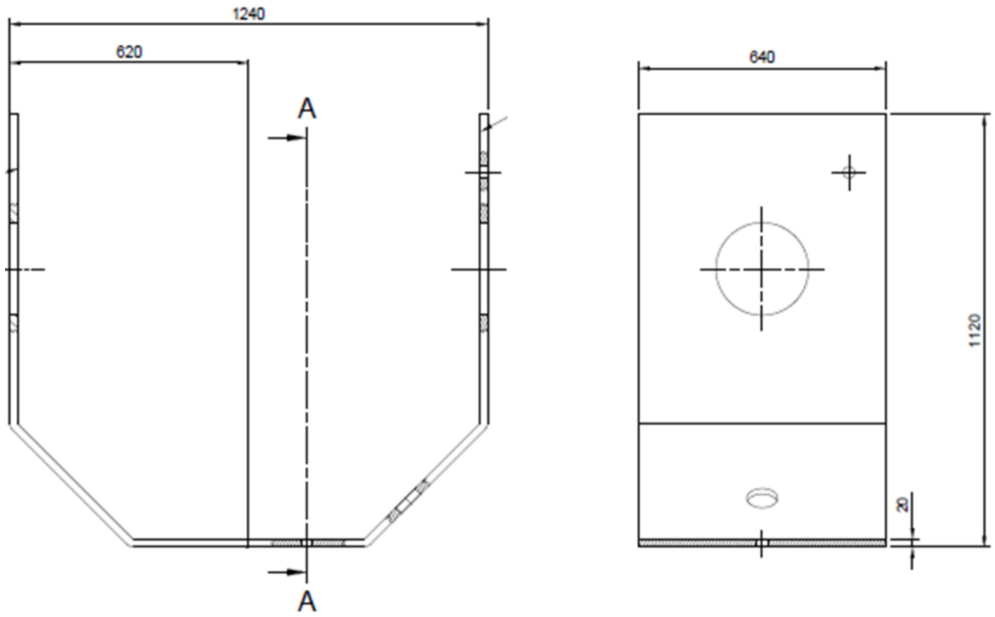


Figure 37 - Proposed design for the housing central wall

Some modifications were also proposed for the preparations required for the welding procedures, but that will be explained in a later chapter.

4.2.2 Housing cover

The housing cover design did not have, unlike its housing counterpart, any problem to be produced using the chosen manufacturing processes. It did, although, have a different problem that could make its manufacturing more difficult, see Figure 38 below.

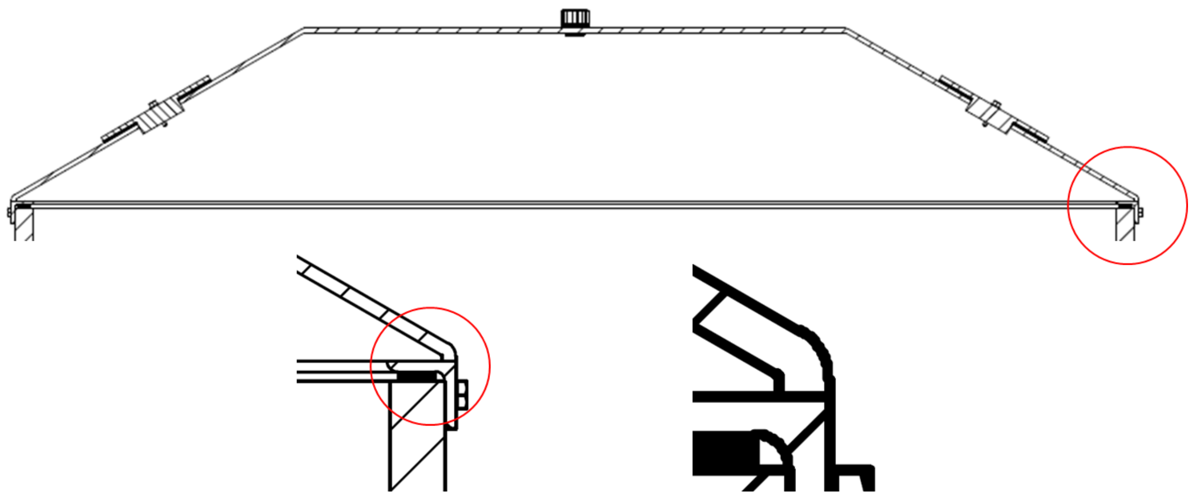


Figure 38 - Housing cover design proposed by Sousa[5]

If we take a look at the end of the housing cover, right where it makes contact with its LPE reinforcement to allow for an easier sealing, we see a final bending with insufficient length to be manufactured (it had around 1.6 mm). There were two ways to deal with this problem, either we:

- Manufactured the final bend using a longer sheet, and them removed the excess material.
- Removed the bend.

Since it poses no threat to the component sealing capabilities, neither created significant stress concentrations on the component, nor made it impossible to weld the component, both final bends were removed.

4.2.3 Encoding the parts

It was seen while analyzing the project that the drawing and the written report could have benefited from a more organized method of identifying the project's components. Since it was predicted that more detailed drawings for every part would be made (thus increasing the complexity of the project), it was deemed necessary to develop a clear way to identify the parts, thus an encoding system was developed that would satisfy these requirements.

The code should be made as simple as possible, but it also needs to identify clearly the assembly and/or sub-assembly that the given part belongs to, so a longer code should be expected if the part belongs to subassemblies.

For a first premise, the prefix ETR01 (ETR-Eolic Test Rig) was added before every single code of component to identify clearly that these components belong to the Wind Turbine Test Rig Gearbox initially projected by Sousa [5] . The codes following this prefix have different meanings. They can be consulted in Table 13 below.

Table 13 - Table of selected codes

Code	**Meaning**
ShX	Shaft number X
SpXX	Spacer number XX
CoXX	Cover number XX
GeX	Gear number X
SeX	Seal number X
AAXX	Assembly of assemblies' number XX
AXX	Assembly number XX
PXX	Part number XX

4.2.4 Ply bending calculation and design

According to the calculation method detailed on chapter 2, a simple method can be used to calculate the dimensions of the metal sheets used to obtain the parts for the housing assembly and the housing cover assembly.

The first requirement for the dimensioning of the sheets is the calculation of the minimum and maximum radius that the steel sheet can take, following the equations 2.5 and 2.7 Table 14 was created:

Table 14 - Calculations for the minimum and maximum radius for bending

T (mm)	20	5
E (Pa)	2,10E+11	2,10E+11
$\boldsymbol{\sigma_{ced}}$ (Pa)	4,70E+08	4,70E+08
$\mathbf{R_{min}}$ (mm)	10	2,5
$\mathbf{R_{max}}$ (mm)	4,47E+03	1,12E+03

From this table, we can have guidelines that allow us to better select a possible bending radius for the sheet metal parts. This is important for the calculation of the total length of the metal sheets and to calculate the length of the sheet section and the positions where the bending tool will contact the metal sheet.

Calculations for the first bend of each part (according to equation 2.4) are presented below (Table 15), followed by the final results for each part (Table 16).

Table 15 - Results for the calculation of the first bend

Part	*T (mm)*	*R_1 (mm)*	*ϕ_1 (°)*	*R_1/T*	*ξ_1*	*Ln_1 (mm)*
ETR01AA1A01P01	20,0	20,0	135,0	1,0	0,41	66,4
ETR01AA1A01P02	20,0	20,0	135,0	1,0	0,41	66,4
ETR01AA2P01	5,0	3,0	150,0	0,6	0,38	12,8

Table 16 - Final results for the bending calculations

Part	*T (mm)*	*L_1 (mm)*	*Ln_1 (mm)*	*L_2 (mm)*	*Ln_2 (mm)*	*L_3 (mm)*	*Ln_3 (mm)*	*L_4 (mm)*	*L_{total} (mm)*
ETR01AA1A01P01	20,0	799,7	66,4	426,7	66,4	299,7	0,0	0,0	1658,9
ETR01AA1A01P02	20,0	799,7	66,4	426,7	66,4	299,7	0,0	0,0	1658,9
ETR01AA2P01	5,0	367,4	12,8	598,9	12,8	367,4	0,0	0,0	1359,4

This allows us to dimension the sheets to be bent, however further calculations need to be made before the manufacturing of these three parts can be fully defined

4.2.5 Welding joints

An appropriate selection of welding joints is vital to the good quality of the welded components. The selection of welding joints is based on the standard ISO 9692[30], since this standard provides the reader with a complete table of welding joint preparations, the recommended sheet thickness that the joint should be used on, and the possible welding procedures to be used.

Only two pre-requisites were given to the welded components, and those were:

- Guaranteeing that the housing is properly sealed and doesn't leak oil or allow impurities inside.
- Being resistant enough to keep the housing together under the normal loads (which aren't significant).

For those two reasons, it was suggested that the welds performed should be complete, thus the total thickness should be welded together, and, when possible, there should be a corrective internal weld, as to guarantee better-quality of construction.

The chosen weld joints are represented in each individual detail drawing, to better elucidate the way that the part should be cut before being welded to the assembly. Also, individual welding drawings were put together for each assembly.

4.2.6 Thermal cutting over thickness

Some points need to be made about correcting a design to be cut using either plasma cutting or oxy-fuel cutting.

The first one is about the needed over-thickness for machining when the part has been cut using any thermal process. An aspect that needs to be accounted for is that the process itself creates irregularities while cutting, also any thermal cutting mechanism creates a heat affected zone that can hinder the mechanical properties of the material, thus creating a zone around the cut that needs to be machined to achieve better results.

The desired over-thickness chosen were based both on a graph supplied by Kjellberg [45] (a thermal cutting machines supplier) and some practical knowledge about the matter, so:

- For the plasma cutting it was chosen an over-thickness of 5mm;
- For the oxy-fuel cutting it was chosen an over-thickness of 10mm;

These are however only for the parts that will be machined later, in the walls that are going to be weld there should be no problem arising from these procedures.

There were also some aspects about internal holes that need some attention. Since the machines need to fuse the material before removing it, there is a minimum amount that needs to be removed before the machine can cut a hole. This problem minimizes the size of the holes that can be cut on the metal sheets before machining. As a rule of dumb, Kjellberg[46] recommends cutting no holes smaller than 1.5 times the thickness of the sheet being cut, so in those situations, the small holes were omitted from the drawings, only appearing for the machining drawings (machining operations are only performed on the final assembly of the housing or the housing cover).

4.2.7 Tolerances and calculation

A lot of contacting elements in this assembly require adequate tolerances to function properly. Fortunately, the standardized parts that are supplied by external suppliers (rolling bearings, seals, etc) have information regarding the required tolerances to be given to the designed parts that contact with them. These are the ones that I started with, these being:

Roller bearings

Almacinha [47] and SKF[48] suggest similar methods to define the appropriate fits for the shaft and the housing. These depend on a correct definition of the load conditions in the roller bearing, and thus thorough analysis of the component should be done prior to the selection of the fits.

First off, the conditions of rotation need to be selected. SKF presents a table that illustrates those conditions. The selected option can be seen on Figure 39, the rest of the table will be annexed for further consultation:

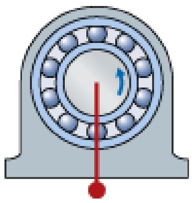
Operating conditions	Schematic illustration	Load condition	Recommended fits
Rotating inner ring		Rotating inner ring load	Interference fit for the inner ring
Stationary outer ring		Stationary outer ring load	Loose fit for the outer ring possible
Constant load direction			

Figure 39 - Operating conditions of the roller bearings and respective recommended fit[48]

So, according to the figure, the housing can have a loose fit but the shaft needs to have an interference fit with the inner ring. Selecting the loose fit is relatively easy, since the recommended ones are H6 or H7, and because it is easier to manufacture the H7, this is chosen for every roller bearing housing.

For the shaft, further analysis to quantify the load is necessary. Almacinha[47] suggests a simpler approach to deal with it, calculating a parameter P/C (P is the load applied to the roller bearing and C is the basic dynamic load rating of the roller bearing) and through that value selecting an appropriate fit for the shaft. Those considerations are presented below on Table 17, along with the calculations for this specific application.

Table 17 - Fit selection method for roller bearing shafts proposed by Almacinha[47] (translated and adapted)

	Diameter	P/C	Recommended fit
Ball Bearings	Up to 40mm	0,07-0,15	j6 (j5)
	40-100mm	≤0,07	j6 (j5)
		>0,07	k6 (k5)
	100-200 mm	≤0,07	k6 (k5)
		>0,07	m6 (m5)
	More than 200mm	0,07-0,15	m6 (m5)
		>0,15	n6 (n5)
Cylindrical Roller Bearings	Up to 60mm	≤0,07	j6 (j5)
		>0,07	k6 (k5)
	60-200 mm	<0,07	k6 (k5)
		0,07-0,15	m6 (m5)
		>0,15	n6 (n5)
	200-500 mm	0,07-0,15	m6(n6)
		>0,15	p6
	More than 500mm	0,07-0,15	n6 (p6)
		>0,15	p6

Table 18 - Calculations for the required fits for the roller bearing shafts

	Roller Bearing	*Ø (mm)*	*P (kN)*	*C (kN)*	*P/C*	*Required fit*
1	NU318ECP	90	51,84	356	0,15	n6
2	NU215ECO	75	18,2	156	0,12	m6
3	NU230ECP	150	50,64	510	0,10	m6
4	NU2230ECM	150	163,7	735	0,22	n6
5	NU2230ECM	150	163,8	735	0,22	n6
6	NU2230ECM	150	175,4	735	0,24	n6
7	6240	150	34,23	270	0,13	m6
8	NU240ECM	200	168	850	0,20	n6
9	NU2244ECML	220	313,9	1570	0,20	p6

Some adaptations to simplify the manufacturing process of the shafts were suggested. Since the n6 fit is required for loads higher than the ones that require an m6 fit, m6's were converted to n6, creating more uniformity for the shafts. Another point about the 9th roller bearing, it's p6 fit designation is in a borderline transition with a n6, so it was perceived that it wouldn't harm the function of the roller bearing if the designated fit was transformed in a n6 fit. To sum it all up, the selected fits for all the roller bearing mounts are n6 fits.

Seals

There are two main standard seal types in this project: O'ring seals and shaft seals.

For both the respective manufacturer gives information about the adequate housing needed for them. The manufacturer SKF (for the shaft seals) tells us the adequate tolerances and surface roughness for all and every seal housing: H8 [49] and between Ra 1.6 to Ra 3.2. [50]

For the measure and the geometry of the housing, they provide Figure 40 that is self-explanatory:

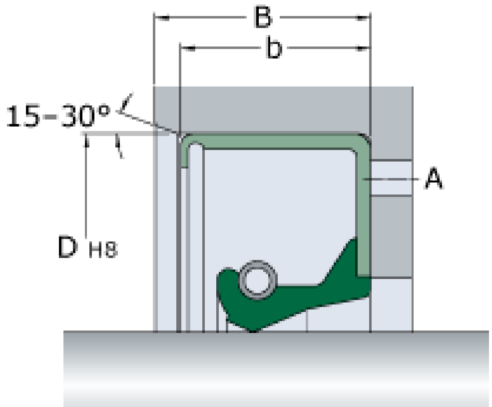


Figure 40 - SKF Seals' Housing geometry requirements[51]

A 15-30º chamfer is required to prevent damages to the seal during installation, the required radii for the chamfer is also given on a table for diameter up to 4000mm[51], that is annexed to this document. Holes (A) should be present to facilitate the removal of the seal.

As for the Parker O'Rings, Parker has published the O'Ring Handbook that compiles all the information required for the housing and installation of their products. The table for the specific cases required for this project will also be annexed.

Spacers and covers

These two components only have to fit (preferably a bit loosely, they are easier to assemble that way) in the shaft (spacers) or hole (covers and spacers) that they contact with.

Since all the holes are H7, it is possible to select a h7 tolerance for the covers (or spacers, if they contact the hole) and to be certain that this solution will guarantee the desired fit. As for the spacers, we need to know that the shafts where they mount have a n6 tolerance associated, so a F7 tolerance was chosen, as it should work for this application. This tolerance was chosen to avoid having the spacers shaking in the shafts when they rotate, but they also need to be mounted easily in the shafts.

Some calculations were made, and the results are presented below on Table 19.

Table 19 - Calculations made to determine the absolute clearance between the shafts and the spacers

	Nº	Ø (mm)	Fit modif. (μm)	IT (μm)	Dev. + (μm)	Dev. - (μm)	Ømin (mm)	Ømax (mm)	Ma. Clear. (mm)	Max Interf. (mm)	Sel. Tol.
Spacer	2	90	36	35	71	36	90,036	90,071	0,048	0,009	F7
Shaft	1	90	23	22	45	23	90,023	90,045			n6
Spacer	4/6	150	43	40	83	43	150,043	150,083	0,056	0,009	F7
Shaft	2/3	150	27	25	52	27	150,027	150,052			n6
Spacer	9	220	50	46	96	50	220,050	220,096	0,065	0,010	F7
Shaft	4	220	31	29	60	31	220,031	220,060			n6

Any other components omitted during this chapter had standardized definitions for their housing, thus their geometry and tolerances were omitted from this text.

4.2.8 Protective Coating (Corrosion Protection)

For a reinforced protection against corrosion, the parts that contact with the outside air should have some kind of surface finishing. These problems about corrosion can compromise the entire functionality of the product if the housing is compromised, either in its sealing properties, or its structural properties.

The problem with a correct definition of the amount of corrosion protection that should be given to a certain product is that it is dependent on the environment where the product will develop its function. I followed the ISO 12944 [52] standard to assess the classes of protection that exist for the protection of steel structures. Table 20 presents the 6 categories and their commonly associated environments

Table 20 - Protective coatings' categories for steel structures[53]

ISO 12944 CLASSIFICATION	TYPICAL ENVIRONMENTS
C1 C2	Heated buildings/neutral atmosphere Rural areas, low pollution
C3	Urban and industrial atmospheres Moderate sulfur dioxide levels Production areas with high humidity
C4	Industrial and coastal Chemical processing plants
C5I	Industrial areas with high humidity and aggressive atmospheres
C5M	Marine, offshore*, estuaries, coastal areas with high salinity

Given that Portugal has a lot of facilities in high salinity areas, I presumed that a C5M degree of protection could be necessary, but the manufacturer is invited to change the degree of protection at will, since in this stage it is not yet clear where the product will be operating.

After choosing the degree of protection, I consulted CIN (a manufacturer of protective coatings in Porto) and they had a list of possible protective coatings for each corrosion category, the one I chose is listed on Table 21.

Table 21 - Protective coating scheme suggested by CIN for C5M protection[54]

Type of paint	Painting scheme	Thickness (Dry)
Zinc rich primer	1 × C-Pox Primer ZN800	75 µm
Epoxy intermediate layer	1 × C-Pox S990 Mio FD	85 µm
Polyurethane	2 × C-Thane RPS HS	80 µm

There are also other alternatives, so I will annex the suggestions by CIN and by another manufacturer for future consultation and to facilitate the search.

4.3 Summary Table of improvements

A brief overlook of the improvements suggested to the original design can be consulted in the table below:

Table 22 - Summary of the proposed improvements to the original design

Number	Designation	Previous design	New design
1	Substitution of the keys with splined shafts	Connection between the gears and the shafts made with keys.	Connection between the gears and the shafts made with splined shafts-
2	Substitution of the screws on the top covers	Emilie Maurin 62434 made of A2 stainless steel.	Emilie Maurin 22401 made of cemented steel.
3	Substitution of the plug	ELESA TSD 40x1.5	ELESA GN742-50-M40x1.5-OS-1
4	Housing changes	Housing has a central wall that was made of one single sheet of steel	Housing has a central wall split in half. Plug position is changed.
5	Housing cover changes	A final bend is present in a internal connection.	The same final bend is removed.
6	Introducing codification	Not available.	Available.
7	Ply bending design	Not available.	Calculation, drawings and tool selection available.
8	Welding joints	Available in some detail drawings.	Available in specialized welding drawings.
9	Thermal cutting over thickness	Not available.	Available and represented in the drawings.
10	Tolerances calculation	Available.	Available and improved
11	Protective coating	Not available	Available

5 Revision of manufacturing processes

Some predictions about the suggested manufacturing process of these components were made. These were made mainly regarding the possible machines that would need to be used or even purchased to manufacture those components, but there are also some considerations about tools and machining parameters to be followed.

These configurations, however, require careful analysis from experts of each manufacturing process, to further optimize and adjust the suggestions.

5.1 Thermal Cutting

A machine needed to be selected that would cut sheets of steel as thick as 160 mm, and as big as 1000X1000mm. That way, a one-size-fits-all approach can be presented, allowing us to reduce the costs with equipment. Another desired feature was to have both plasma cutting and oxy-fuel cutting, since only those two thermal cutting procedures were suggested to manufacture the components.

The chosen equipment was the ESAB Combirex DX. This equipment, besides combining both plasma and oxy fuel cutting and having the required working area dimensions, is a CNC cutting machine, so it can be programed to cut the components with higher precision, speed and it is more efficient at achieving high production rates.

More information about the machine will be annexed for future consultation.

5.2 Welding

There are only two parts that require the intervention of welders, the housing, and the housing cover. Fortunately, both of those components are made of the same material, St52. This steel is the one that is suggested by Ramada for welded components.

Due to the amount and size of welds that need to be produced, it was suggested by Eng. Nuno Lopes that MAG welding would be the most suitable alternative, due to its versatility and high rate of deposition.

The only thing that is left is to choose an appropriate filler metal for the application. To do that first the base metal's composition was analyzed, and a filler with an approximate chemical composition to the base metal (from the ones that can be used for MAG welding) was selected. The composition of St52 is:

Table 23 - Composition of St52 Ramada[55]

	C (%)	Si (%)	Mn (%)	P (%)	S (%)	Cu (%)	N (%)
St 52	0,22	0,55	1,6	0,03	0,03	0,55	0,012

Knowing the material's composition, ESAB's catalog of filler metals for MAG welding was consulted, and the chosen filler metal was the OK AristoRod 12.62 with a diameter of 1.2 mm for the housing (because of the 20mm thickness of the housing's walls) and a diameter of 0.9mm for the housing cover (the thickness of the steel plies is only 5mm, thus a smaller diameter should be better for this application).

Since the welding parameters are dependent on the thickness of the filler metal, two different ranges of parameters are suggested for this project:

Table 24 - Welding parameters suggested by ESAB

Diameter, mm	**Wire feed, mm/min**	**Welding Current, A**	**Arc Voltage, V**	**Deposition rate kg/hour**
1.2	2.5-15	120-380	18-35	1.3-8.0
0.9	3-12	70-250	18-26	0.8-3.3

The welding parameters supplied by ESAB are meant to be adapted to the conditions faced when the welding takes place, so only a range of values can be suggested. The values should be adapted by the welders, relying on their experience on the subject.

Annexed to this document is the information supplied by ESAB about this product, and their consultation is suggested.

5.3 Bending

Although a previous calculation of sheet lengths and bending radius was already determined, it is still necessary to choose appropriate tools and dies to bend the sheet to the desired shape, and calculate the necessary forces.

A calculation table (Table 25) based on the equations (2.8-2.11) was made, and its values adjusted so that the manufacturing might be possible.

Table 25 - Force calculations for the sheet metal bending

Part	*k*	*n*	*σ_{max} (Pa)*	*b (mm)*	*T (mm)*	*M (Nm)*	*Ri_1 (mm)*	*Rk_1 (mm)*	*ϕ_1 (º)*	*lk_1 (mm)*	*F1 (kN)*	*F1/b (KN/m)*
ETR01AA1 A01P01	1,3	1,8	4,70E+08	640,0	20,0	54144,0	20,0	20,0	135,0	140,0	1088,6	1701,0
ETR01AA1 A01P02	1,3	1,8	4,70E+08	640,0	20,0	54144,0	20,0	20,0	135,0	140,0	1088,6	1701,0
ETR01AA2 P01	1,3	1,8	4,70E+08	678,0	5,0	3584,9	3,0	4,0	150,0	32,0	108,9	160,7

A few points need to be made:

- For an appropriate selection of tools, two parameters should be considered. First is the total width of the sheet (b), that requires the tool to be larger than that value. The second one is the Force per meter generated during the bending process, which needs to be less than the maximum value given by the tool supplier.
- RolleriTools was selected as a possible tool supplier but their heavy-duty tools (that can take up to 4000kN/m of maximum force per length) only go up to 500 mm of length, so either two tools are used simultaneously, or the parameter lk needs to be augmented for the first two parts, as to allow the usage of a less resistant tool.
- For the third part, there was no problem selecting appropriate tools and dies since the force values involved are low.

The selected tools and dies for the job were:

- ETR01AA2P01:
  - Tool: Rolleri tools 01630-835mm (R=3mm; L= 835mm)
  - Die: Rolleri tools M60.85.32 (R=4mm; L=835mm)

- ETR01AA1A01P01/P02:
    - Tool: Rolleri tools RHDP.60.20-250 – 2x500mm (R=20mm; L=1000mm)
    - Die: Rolleri tools AD65.185 (R=20mm; L= 1000mm)

As for the bending machine chosen, any machine that can utilize the chosen tools and develop more than 1100 kN of force to the sheet can be utilized. Since ADIRA is well known to the engineering students of FEUP and its manufacturing facilities are located in Porto, the chosen machine was from their catalogue. The chosen machine is then GUIMADIRA PM 13530, having a working length of 3000mm (more than enough for the metal sheets being manufactured), and a bending capacity of 1350kN.[56]

5.4 Machining

Every non-standard component requires, to some degree, machining operations to achieve the final shape. To perform a machining operation to any component some information needs to be collected, namely the total dimensions of the component, an estimate of the total weight and the material.

After this information is collected/calculated a machine can be pre-selected to machine this part. This is however a first approximation, because some aspects are being overlooked, like the CNC machine's production capacity while performing those machining operations. So, a more thorough analysis might be necessary if mass production of a component is desired.

Eng. Nuno Lopes suggested three empirical criteria to be able to quickly select a lathe machine:

- **Length criteria:** If a component is bored through its entire length, then the lathe requires at least twice the length of the component. If it is solid, then only 1.4 times its length should be necessary.
- **Diameter criteria:** The Lathe should have at least the diameter of the component plus 150mm (it is approximately the size of a Tool holder) to machine the component adequately.
- **Mass Criteria:** HAAS has an internal sheet of the maximum weight of the machined part that they recommend for a certain lathe. That value was compared with the approximation for the weight of each component to select an appropriate CNC lathe.

Another important criterion was the price of the CNC machine. Since usually the more expensive alternative is capable of machining the components that the cheaper option machines, the cheaper option will always be chosen in favor of the more expensive one, but it is given information that an equivalent or better machine should be able to perform just as well as the machine chosen.

A table was elaborated synthetizing all of those factors, and it is presented below, Table 26:

Table 26 - Selection and calculation of CNC Lathes

Part	***Total Length (mm)***	***Max. Diameter (mm)***	***Required Length (mm)***	***Required Diameter (mm)***	***Part's Weight (kg)***	*Selected Lathe*	*Max. Diameter-Machine (mm)*	*Max. Length - Machine (mm)*	*Max. Weight - Machine (kg)*
Sh1	777,5	100	1088,5	250	40	ST40	648	1118	907
Sh2	680	162	952	312	101	ST40	648	1118	907
Sh3	606	162	848,4	312	90,4	ST40	648	1118	907
Sh4	1057	228	1479,8	378	315,5	ST40L	648	2032	907
Ge1	140	140	280	290	6	ST10	356	406	32
Ge2	140	483	280	632	103	ST40	648	1118	227
Ge3	210	245	420	395	33,1	ST30Y	533	660	113
Ge4	210	862	420	1012	514,17	Mega Turn 1600 M	1650	1140	
Co1	30	245	60	395	6,5	ST30	533	660	113
Co2	20	200	40	350	2,8	ST10	356	406	32
Co3	34	340	68	490	12	ST30	533	660	113
Co4	29	340	58	490	12,66	ST30	533	660	113
Co5	20	340	40	490	8,4	ST30	533	660	113
Co6	30	470	60	620	21,23	ST40	648	1118	227
Co7	45	480	90	630	30,3	ST40	648	1118	227
Co10	20	280	40	430	3	ST30	533	660	113
Sp1	36	190	72	340	3	ST10	356	406	32
Sp2	35	110	70	260	0,9	ST10	356	406	32
Sp3	104	130	208	280	2,3	ST10	356	406	32
Sp4	42	170	84	320	1,7	ST10	356	406	32
Sp5	41	182	82	332	1,7	ST10	356	406	32
Sp6	31	170	62	320	1,2	ST10	356	406	32
Sp7	27	270	54	420	2,5	ST30	533	660	113
Sp8	49	270	98	420	4,6	ST30	533	660	113
Sp9	35	240	70	390	1,2	ST30	533	660	113

As a side note, the Mazak Mega Turn 1600 M is a vertical lathe, while the others are horizontal lathes. The reason it was chosen was because ETR01Ge4 was a large and heavy cylinder, thus a horizontal lathe would struggle with it.

There are only two components that are machined and are not present on the table, the housing and the housing cover. These, because of their shape (quadrilateral shape) are better suited to be machined on a vertical machining center. The machining center chosen for the application was a HAAS EC 1600 with an optional rotation table, to allow a better positioning of these components.

After selecting the machines, it is interesting to evaluate how expensive the initial investment in machines would probably be like, the calculations are presented in Table 27.

Table 27 - Price calculation of the selected CNC machines

Machine	*Brand*	*Base price (€)*	*Required Optionals (€)*	*Extra (for tools) (€)*	*Final expected Investment (€)*
ST-10	HAAS	37995	26680	10000	74675

ST-30	HAAS	55995	14185	10000	80180
ST-30Y	HAAS	80995	14185	10000	105180
ST-40	HAAS	99995	44380	10000	154375
ST-40L	HAAS	143995	36485	10000	190480
Mega Turn 1600 M	MAZAK	540800	0	10000	550800
EC- 1600	HAAS	181995	37095	10000	229090

The bottom three ones are those that are mandatory for this project, that means that the more demanding components cannot be manufactured using less robust machines, while the other components could all be manufactured using the HAAS ST-40L CNC lathe.

Although the selection of the machine is important, it is also necessary to select the appropriate initial material block that is going to be machined to get the component. This depends on a lot of factors, like the familiarity with the company that supplies the block (if it is supplied) or the over-thickness that is required when produced by thermal cutting/other means. For a safety margin, it was considered a general over-thickness of about 10mm for all applications. After having more information about the manufacturing process, these first considerations should be adjusted to achieve better productivity in this process, and less wasted material per component.

A point should be made about the machining of the splined hubs on the gears. Those, for their shape, are meant to be manufactured using a broaching machine since it is the appropriate machine to manufacture those geometries. To select the broaching machine, we are concerned mainly about the size of the working table, to accommodate the components that are going to be machined. The selected broaching machine was the Ohio Broach RP/224 because it was one of the few catalogued models that could perform the desired job, but a custom machine can also be purchased if desired.

Finally, to be able to machine one of the components it is also necessary to create a machining sequence and to select appropriate tools for the job. Those two tasks were completed for one component (and coded, using CAM programming) and will be explained in a separate chapter.

5.5 Standard presentation for each component

A lot of information needs to be given for each component to be produced. This information is required to be synthetized properly to be analyzed and discussed between teams of engineers that will develop each component, but also needs to be distributed between the different production departments that will handle the different steps to manufacture the component.

The solution then is to create a presentation sheet that can quickly give some information about the different manufacturing sequences/processes and the suggested order that they should be done to manufacture the component.

The presentation sheet will be composed by:

- A first section to identify the component and the component’s material.
- A second section to identify the manufacturing processes and to define their assumed order. About each manufacturing processes some information will be given:
    - For thermal cutting the machine, and the thickness of the steel.
    - For welding, the welding parameters, and the filler material.
    - For sheet metal bending, the tools, and the machine.

  - For the surface finishing/protective coating application, the sandblasting grade and the sequence of products to be applied.
  - For grinding, some geometrical information, and specifics about the job.
  - For heat treatment, a suggested method, and the heat treatment proposed by the manufacturer.
  - For machining, the machine, the tools (when applicable), the machining sequence (when applicable) and the initial block.
- The third and last section directs the viewer to the drawings that should be consulted for that component.

Some examples of these manufacturing sheets will be annexed to this thesis as an example of their content.

6 Technical drawings of equipment

In this chapter some details about the drawings will be presented and some examples annexed.

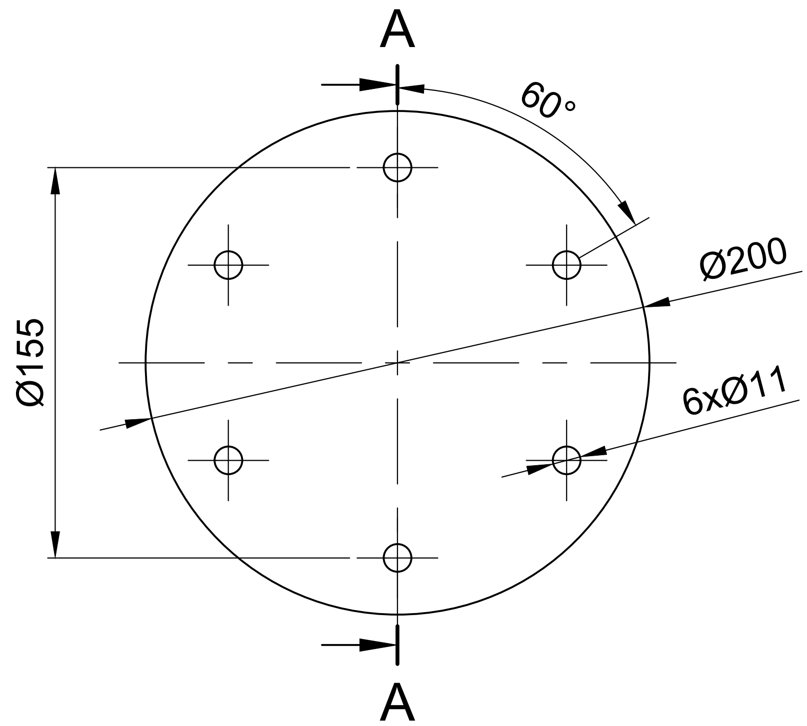
But first, a few remarks:

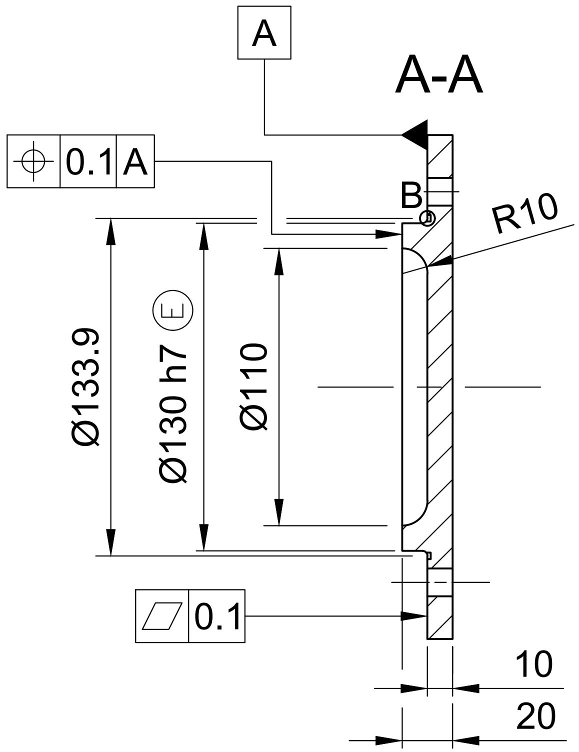
- The Assembly drawing will be divided in two, one cut drawing, one view drawing. This was done to simplify the way the information is presented, since the assembly is quite complex.
- Some components required different manufacturing processes to be properly manufactured, so different drawings were developed in some cases that simplify the reading of each procedure.
- The drawings can, and should be used as a support for the manufacturing sheets that accompany them.

In the next sub-chapters, some representative drawings are presented.

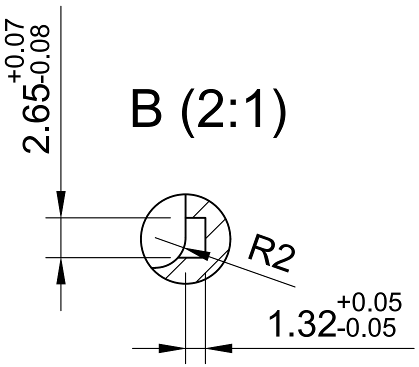
6.1 ETR01Co02-Cover – Number 34

The reasons behind this drawing being chosen are that it represents the components that are rather simple and are obtained using only machining. This component also has a protective coating that can be seen on a table.





B (2:1)



Ra 3.2

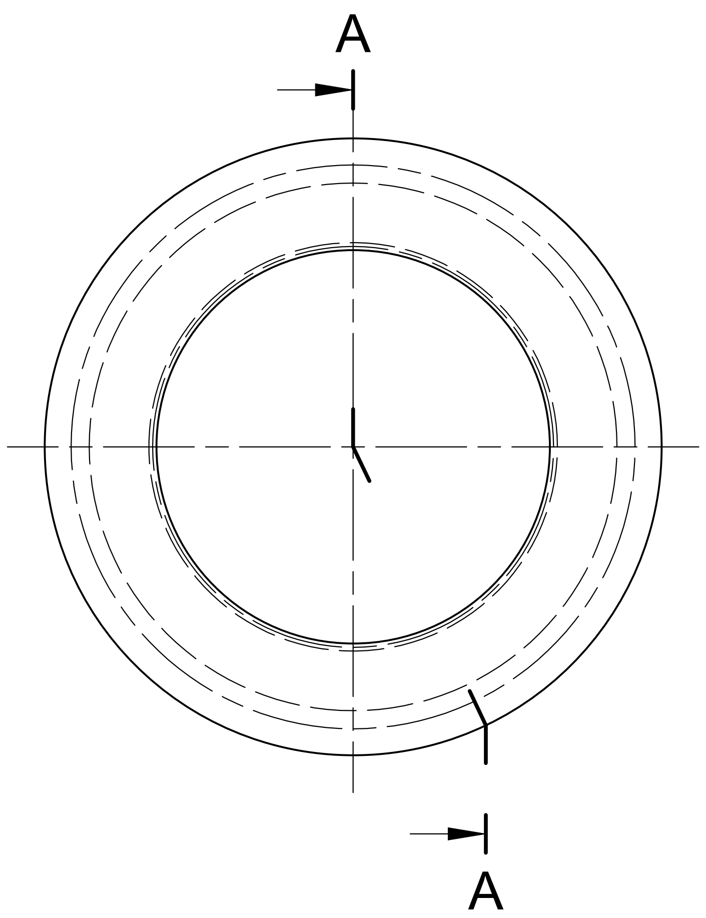
Surface Finish		
Sand Blasting Grade	Sa $\frac{1}{2}$	ISO 8501-1
Primer	1xC-Pox Primer ZN800	75 μm
Intermediate	1xC-Pox S990 Mio FD	85 μm
Top Coat	2xC-Thane RPS HS	80 μm

Legal Owner FEUP	Partners HAAS Factory Outlet	Created by Luís Araújo 23/06/2017	Approved by
Scale 1:3	Tolerances according to: ISO 8015	Document type Detail drawing	Additional Info Aprox. Weight: 2.8 kg Surface Area: 0.07717 m2
Sheet type ISO A4	General tolerances according to: ISO 2768-m	Title ETR01Co02 - InShaft Cover	Material C1 Ramada DIN 9 SMn 36 K/28 K
			Document status
			DWG No. PT000028
			Sheet 1/1

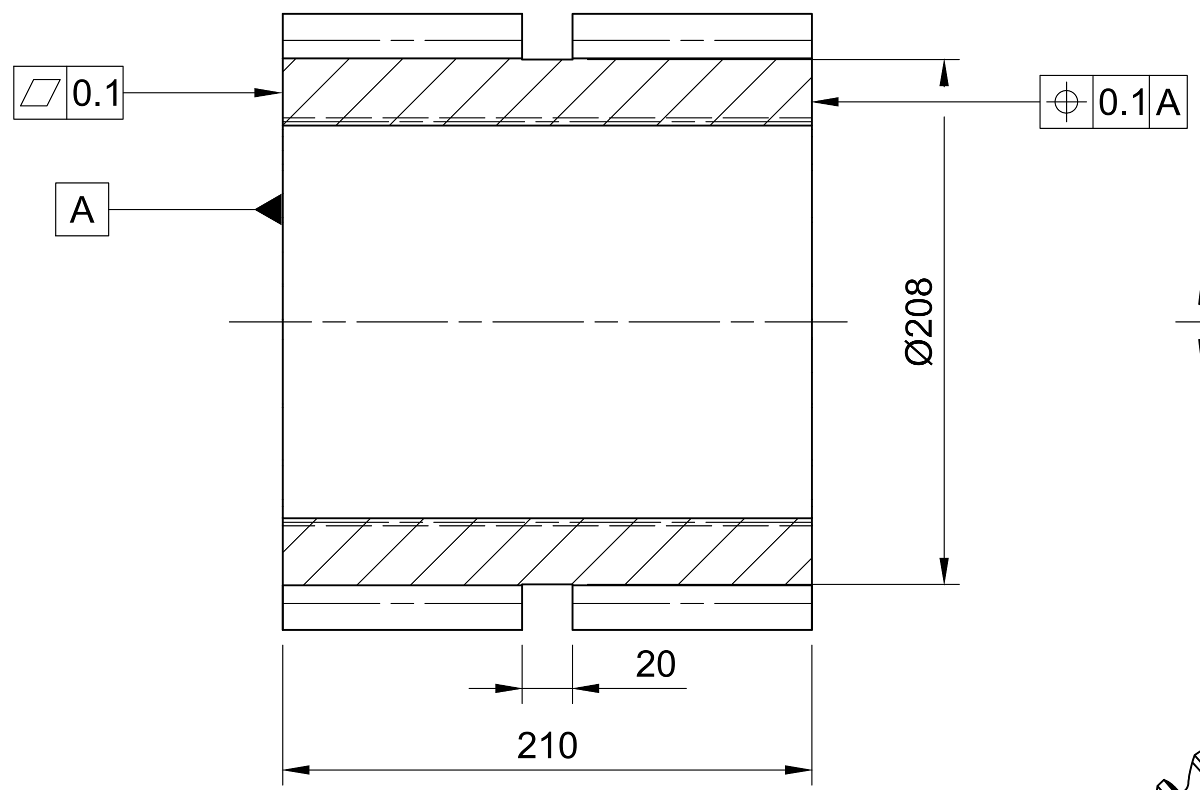
6.2 ETR01Ge03- Z3 Gear – Number 49

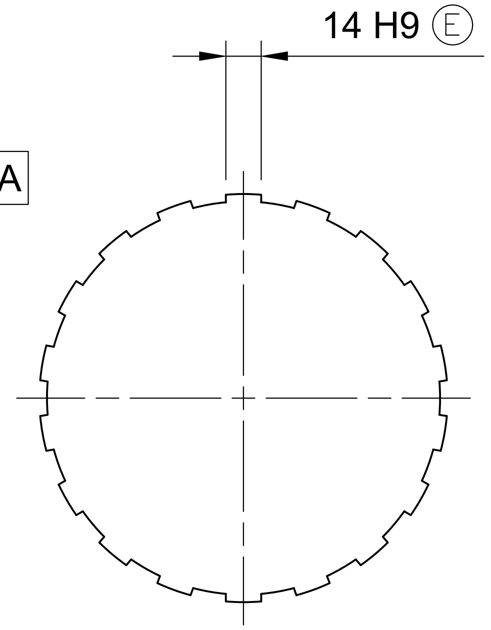
Even though the manufacturing process behind obtaining the gears is also pretty much only machining, some details about these mechanical components need to be present in the drawing.

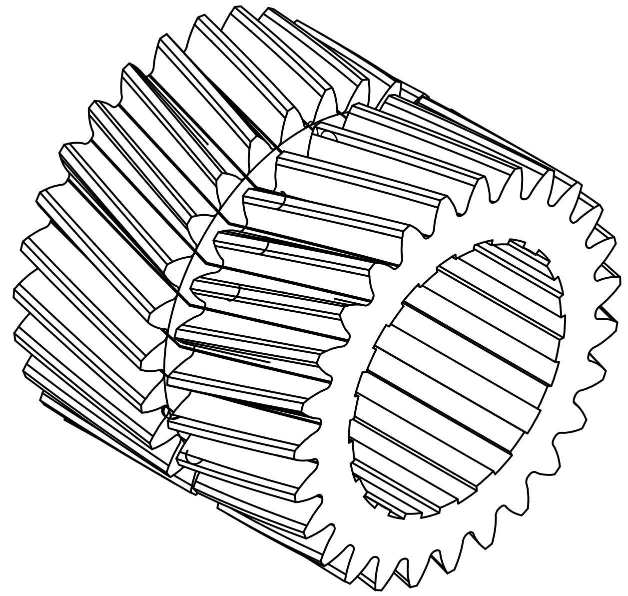
In this drawing can be seen a table synthesizing the characteristics of the gear and one table synthesizing the characteristics of the splines.



A-A



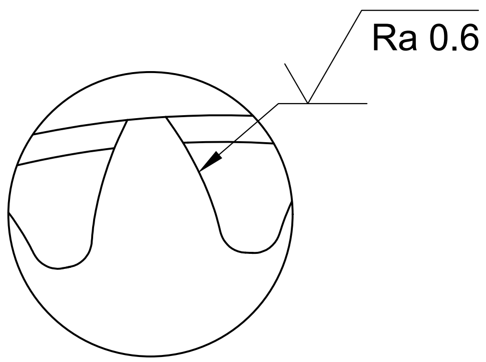




Spline Characteristics	
Type	Straight edge teeth
Number of Teeth	18
Tooth Width	14 mm
Tooth Height	3 mm
Base Diameter	156 mm

Gear Characteristics	
Module	8 mm
Number of Teeth	27
Pressure Angle	20º
Helix Angle	15º
Facewidth (Gap)	210 (20) mm
Reference Diameter	223.620 mm
Root Diameter	209.257 mm
Tip Diameter	244.657 mm
Tip Diameter Allowances	0/-0.01 mm
Accuracy Grade	6 - DIN3961:1978
Profile Shift Coef	0.323 mm
Tip Relief Coefficient	90 μm
Tip Relief Height	7.09 mm
Mating Gear	ETR01Ge4-Z4
Mating Gear Teeth	102

Tooth Profile (1:1)



Ra 1.6

Legal Owner: FEUP	Partners: HAAS Factory Outlet	Created by: Luís Araújo 23/06/2017	Approved by
Scale: 1:3	Tolerances according to: ISO 8015	Document type: Detail drawing	Additional Info: Aprox. Weight: 33.1 kg; Material: G15 Ramada DIN 17 CrNiMo 6
Sheet type: ISO A3	General tolerances according to: ISO 2768-f	Title: ETR01Ge3 - Gear z3	Document status
			DWG No. PT000050
			Sheet 1/1

6.3 ETR01AA1 - Sub-Assembly Drawing – Number 5

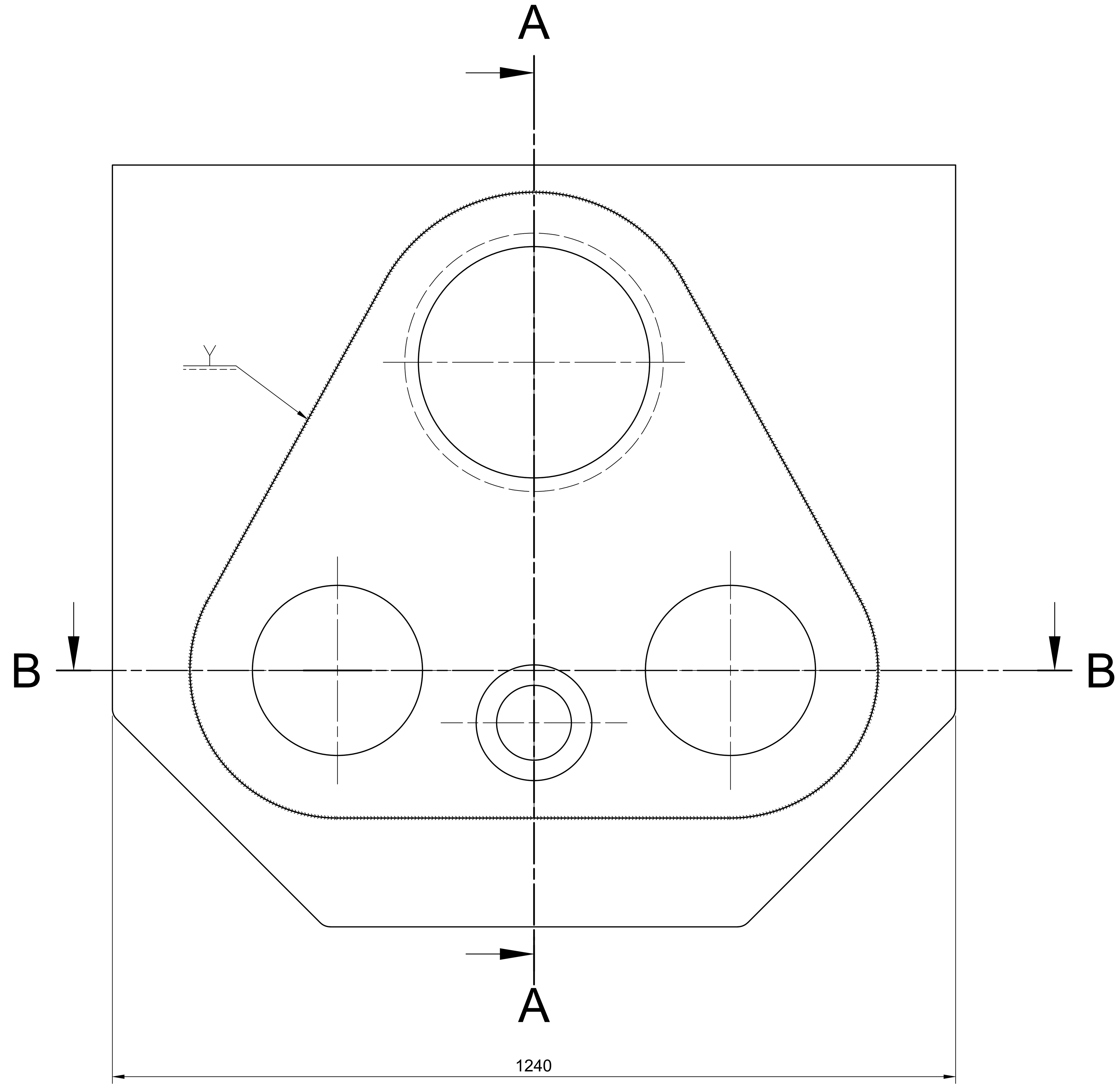
This drawing is exposed to exemplify the kind of after-welding machining that should be done on these kinds of parts. As we can see here, the welding annotations are not indicated, since it is presumed that on this stage the welding is already done, thus we only need machining annotations.

Item	Qty	Name	Material
5	1	ETR01AA1P04	DIN St 52-3 U
4	1	ETR01AA1P03	DIN St 52-3 U
3	1	ETR01AA1P02	DIN St 52-3 U
2	1	ETR01AA1P01	DIN St 52-3 U
1	1	ETR01AA1A01	DIN St 52-3 U

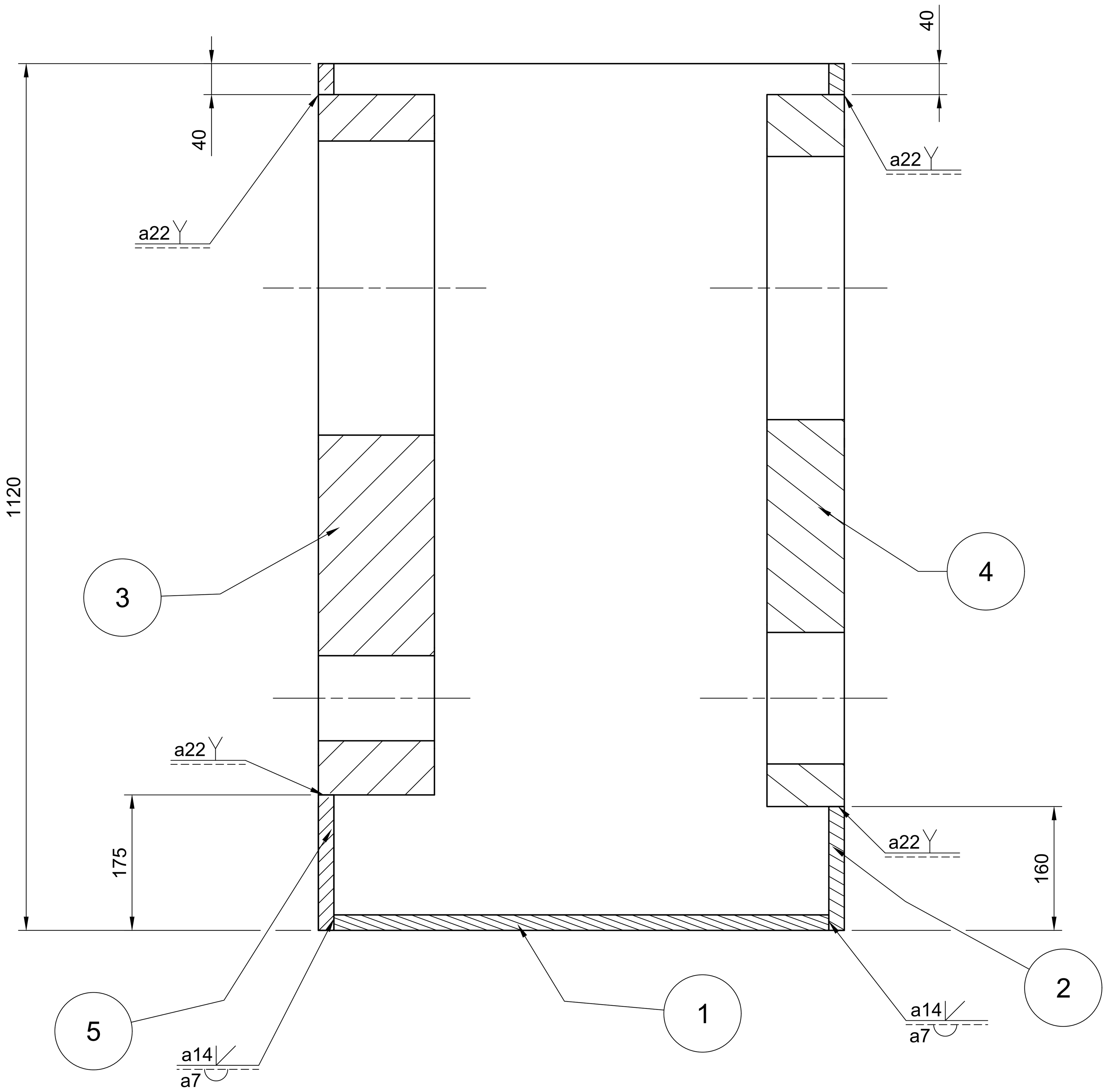
Legal Owner: FEUP	Partners: HAAS Factory Outlet	Created by: Luís Araújo 23/06/2017	Approved by:
Scale: 1:5	Tolerances according to: ISO 8015	Document type: Sub-Assembly drawing	Additional Info: Aprox. Weight: 1280 kg; Surface Area: 10.48 m2 — Material: St 52 Ramada DIN St 52-3 U
Sheet type: ISO A0	General tolerances according to: ISO 2768-m	Title: ETR01AA1 - Housing Assembly	Document status:
			DWG No.: PT000003 — Sheet 1/4

6.4 ETR01AA1 - Welding Drawing – Number 5

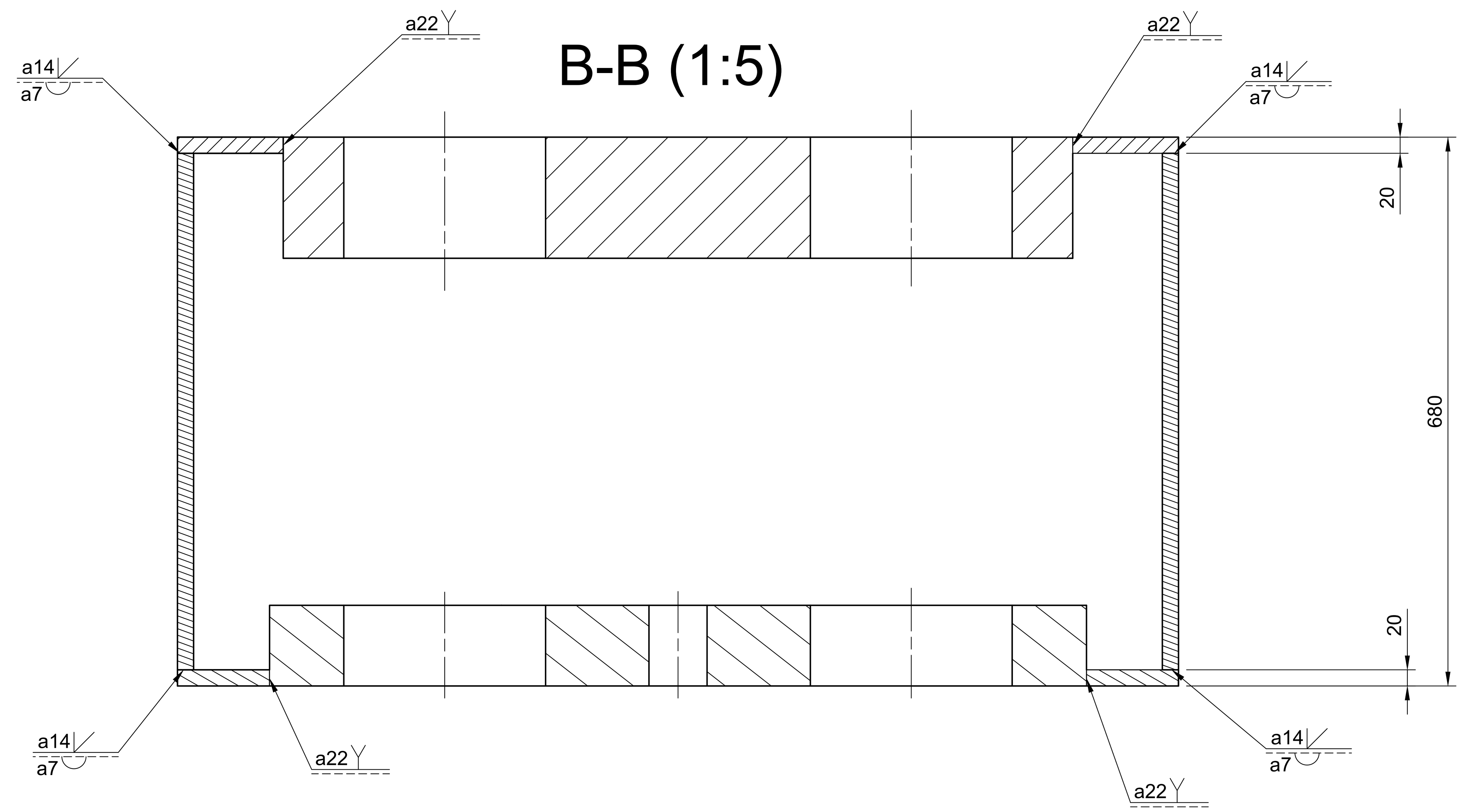
Welding drawings should not be made complicated, as to be easily read by welders on-site. So, this drawing only contains annotations about the welding procedure itself and the required dimensions to position the parts correctly.

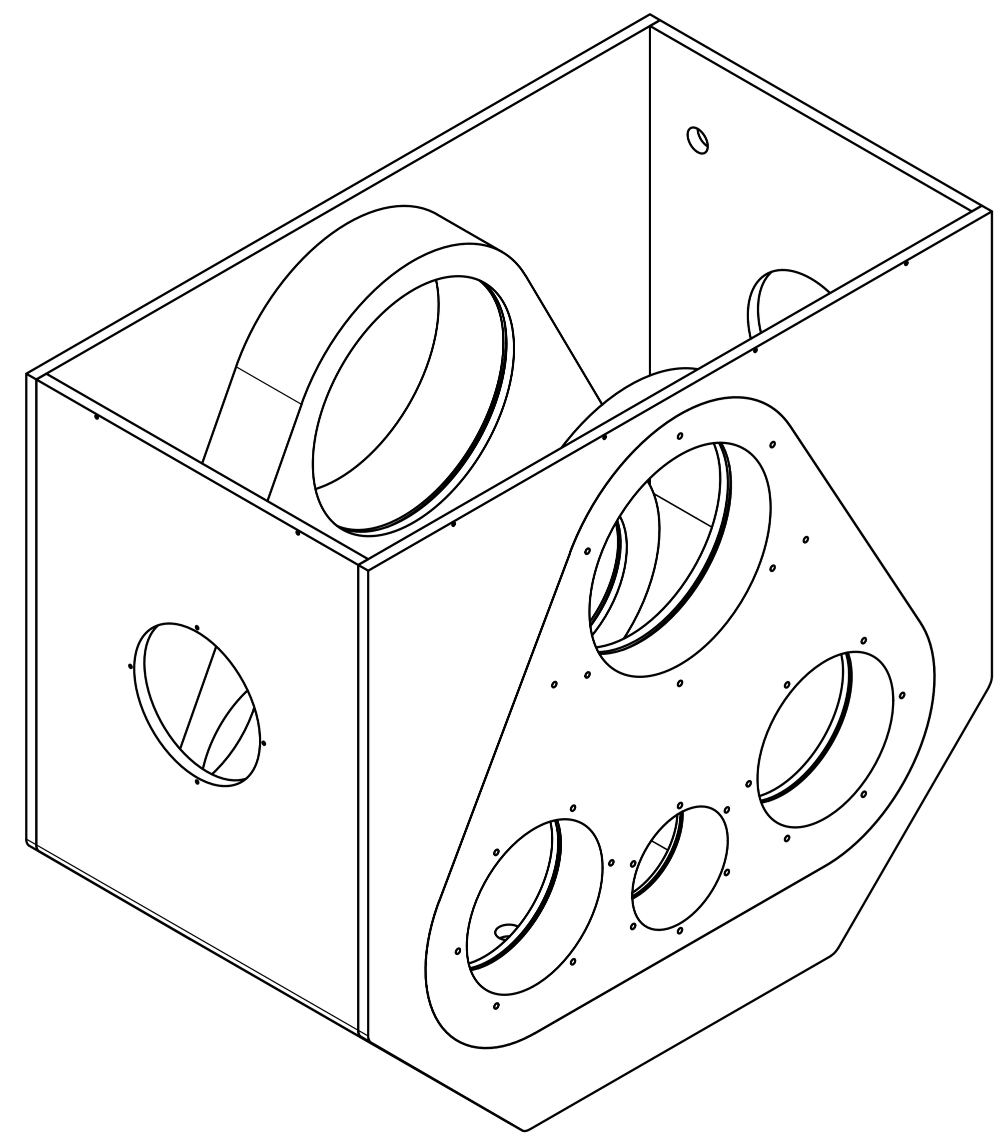


A-A (1:5)



B-B (1:5)



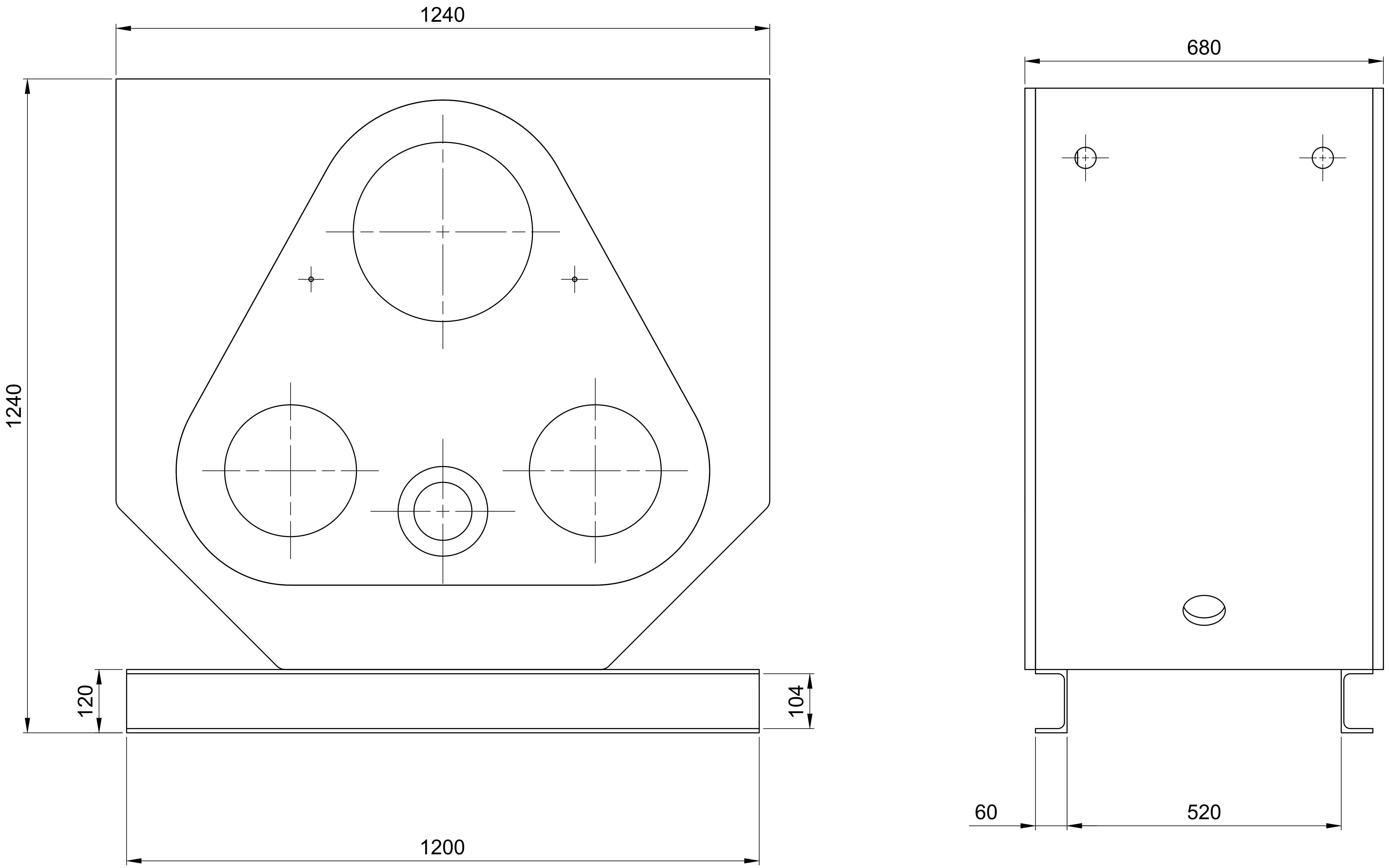


Item	Qty	Name	Material
5	1	ETR01AA1P04	DIN St 52-3 U
4	1	ETR01AA1P03	DIN St 52-3 U
3	1	ETR01AA1P02	DIN St 52-3 U
2	1	ETR01AA1P01	DIN St 52-3 U
1	1	ETR01AA1A01	DIN St 52-3 U

Legal Owner: FEUP	Partners: HAAS Factory Outlet	Created by: Luís Araújo 23/06/2017	Approved by
Scale: 1:5	Tolerances according to: ISO 8015	Document type: Sub-Assembly welding drawing	Additional Info: Aprox. Weight: 1280 kg; Surface Area: 10.48 m2 / Material: St 52 Ramada, DIN St 52-3 U
Sheet type: ISO A1	General tolerances according to: ISO 13920	Title: ETR01AA1 - Housing Welding	Document status
			DWG No. PT000004
			Sheet 2/4

6.5 ETR01AA1 - Surface Finish Drawing - Number 5

Surface finishing is giving the component a protective coating to shield it against corrosion from external sources. A table containing the desired coating is presented, along with some general dimensions of the component to be coated. The total surface area is given to quickly elaborate budgets for the procedure.

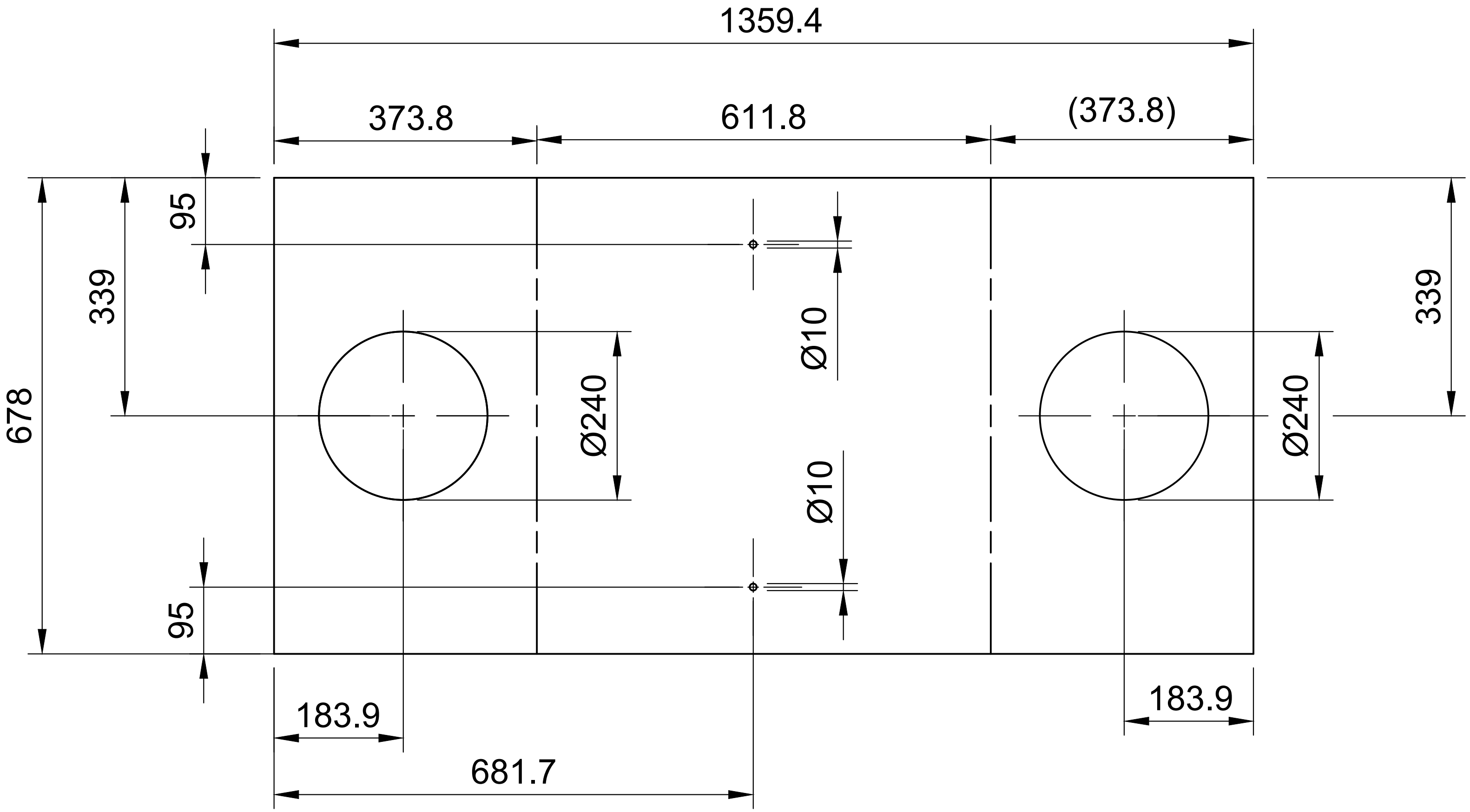


Surface Finish		
Sand Blasting Grade	Sa $\frac{1}{2}$	ISO 8501-1
Primer	1xC-Pox Primer ZN800	75 μm
Intermediate	1xC-Pox S990 Mio FD	85 μm
Top Coat	2xC-Thane RPS HS	80 μm

Legal Owner: FEUP	Partners: HAAS Factory Outlet	Created by: Luís Araújo 23/06/2017	Approved by
Scale: 1:8	Tolerances according to: ISO 8015	Document type: Sub-Assembly surface finish Drawing	Additional Info: Aprox. Weight: 1309 kg; Surface Area: 11.0347 m2 — Material: St 52 Ramada DIN St 52-3 U
Sheet type: ISO A3	General tolerances according to: ISO 13920	Title: ETR01AA1 - Surface Finish	Document status
			DWG No.: PT000006
			Sheet: 4/4

6.6 ETR01AA2P01 – Bending Drawing

A bending drawing is a simple sheet that should be used during thermal cutting and sheet bending procedures. These contain the desired dimensions of the part to be cut along with indication lines of were the bending should be done. Those dimensions are the calculated dimensions of the process.



Legal Owner FEUP	Partners HAAS Factory Outlet	Created by Luís Araújo 23/06/2017	Approved by	
Scale 1:10	Tolerances according to: ISO 8015	Document type Bending Diagram drawing	Additional Info Aprox. Weight: 32 kg	Material St 52 Ramada DIN St 52-3 U
Sheet type ISO A4	General tolerances according to: ISO 9013	Title ETR01AA2P01 - Bending Diagram	Document status	
			DWG No. PT000021	
				Sheet 2/2

7 Machining and prototyping - ETR01Co02

Since all the components in this project will be machined, even if only for some finishing touches in some cases, it is important to understand the additional work required in this field.

To be able to better understand the ramifications of this procedure, the full machining process was explored for this component, ETR01Co02 (Figure 41).

Figure 41 - ETR01Co02, shaft cover.

The first step was already taken for every component of this project, defining a machine and the chosen stock setup. For this component it was predicted that a HAAS CNC Lathe ST-10 would be adequate to machine it properly, the stock used was a cylinder of 220mm of diameter and a length of 40mm.

Now, having the stock and the machine defined, it was necessary to develop a logical machining sequence that could manufacture this cover. To develop it correctly, it is required a brief revision of the different operations that can (and can't) be done on a turning lathe (see Figure 14, chapter 2.1.3, for a quick revision) and adapt the right procedure.

Following these basic principles, most of the desired component can be produced. Although, there are two operations that can't be machined using traditional turning operations, so they require one of two options:

- A different machine is used, specifically a machining center, to open the holes and the seal slot.
- Live tooling is used, thus allowing the machining of the holes and the slot.

The second option was taken, since it will create a more productive approach to the problem.

The machining sequence annexed to this report was developed having this approach in mind. Another important information was that finishing over-thickness was set as 0.1mm, since it was deemed sufficient to obtain the desired results.

After creating a logical machining sequence, appropriate tools and cutting parameters need to be selected. For that, a tool selection software (developed by Sandvik Coromant) was used that, after selecting the parameters and desired results for the operation, calculates the optimal tool and cutting parameters to be used. Some other tools were suggested as alterations by Gabriel Correia (HAAS collaborator, with experience in CNC machining).

The only thing that is left is to program the machine to manufacture the component. To do that, this project had the assistance of Gabriel that, using Fusion software, created a program to follow the instructions that were specified in the annexed machining sequence.

First off, it is required to define the stock that is going to be machined. In the Fusion interface, that menu looks like this (Figure 42).

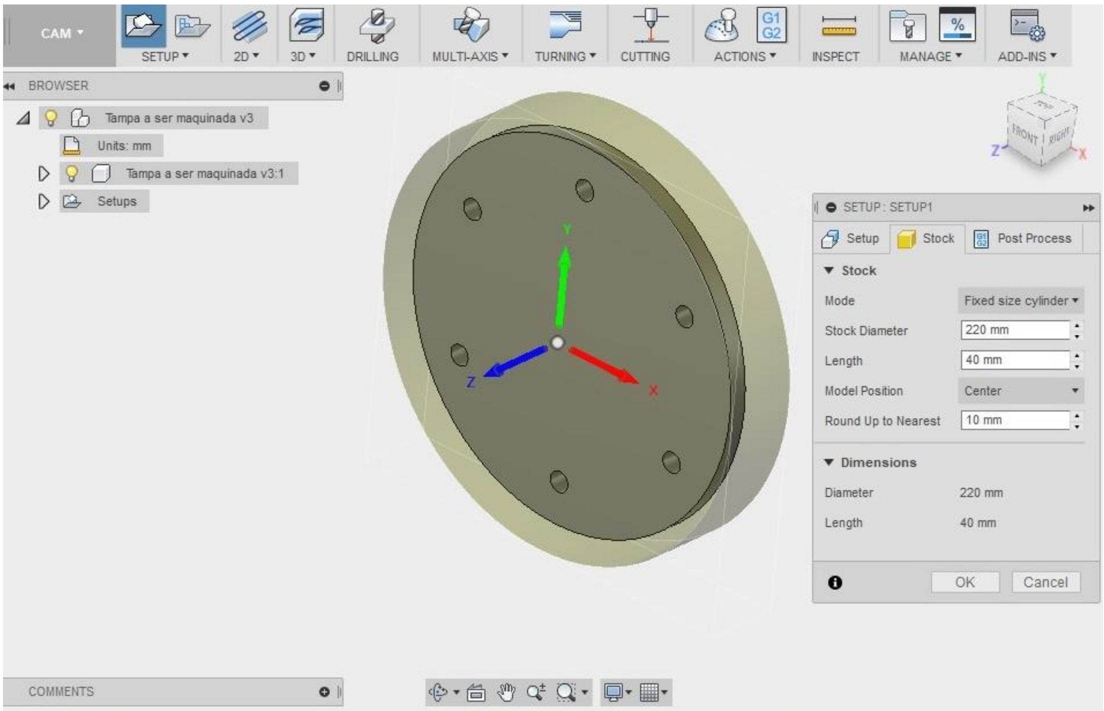


Figure 42 - Stock definition on the Fusion interface

Now, the programming method for the first operation (Facing 9.8mm using roughing parameters) is going to be explained. To start programming this, we need to choose the operation “Turning Face” operation in the “Turning” menu. Then, the interface shown should be something like this:

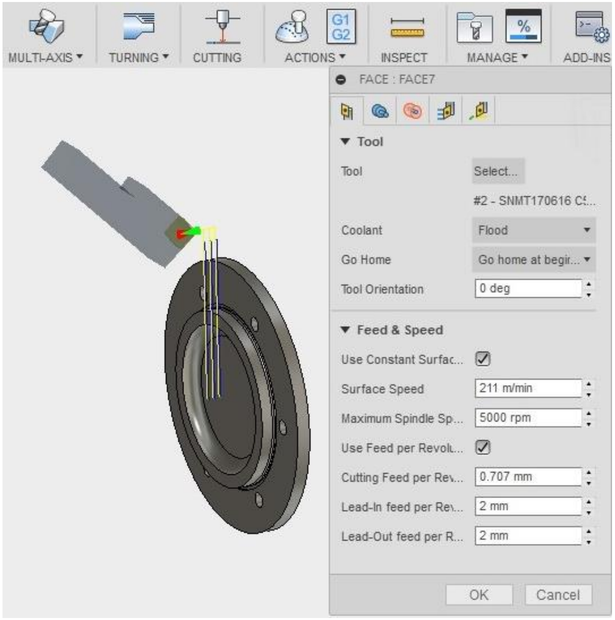


Figure 43 - Turning Face interface in Fusion

The parameters and the tools are not selected yet (the Figure 43 was captured when those were already selected) at this point, so they need to be selected. The tool selection is first and the next menu should appear.

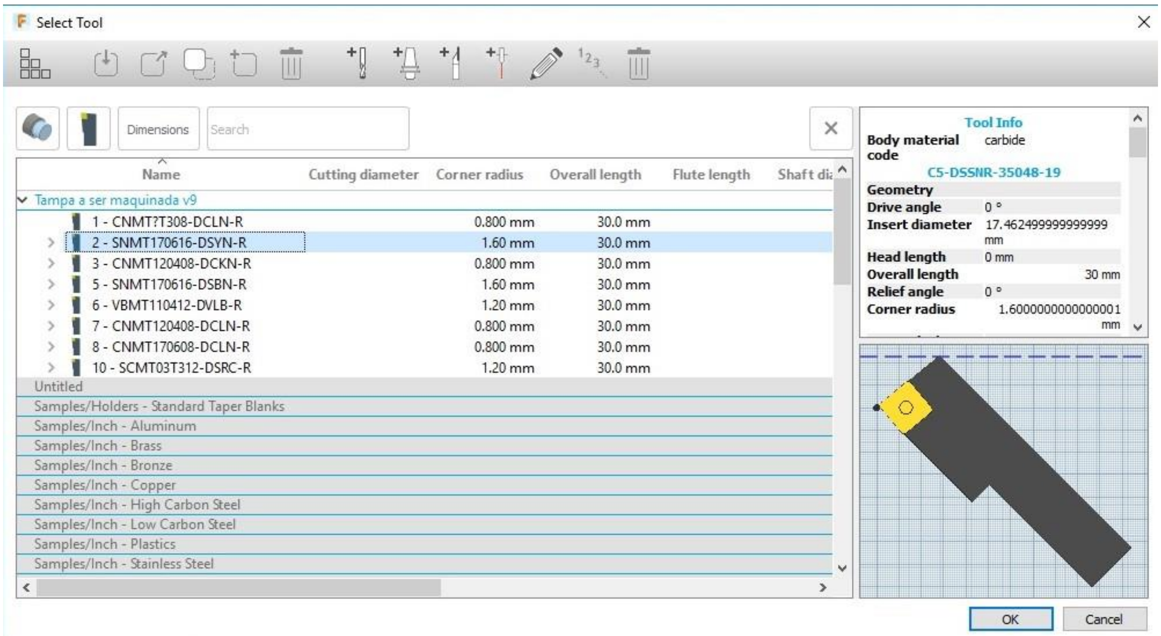


Figure 44 - Tool selection menu in Fusion 360

Some standard tools and some vendors are already available for selection, but since Sandvik is not yet one of those vendors, each selected tool needs to be manually inserted in the program. For that to happen, it is required to press the “+ turning tool” button, and that opens the “add tool menu”.

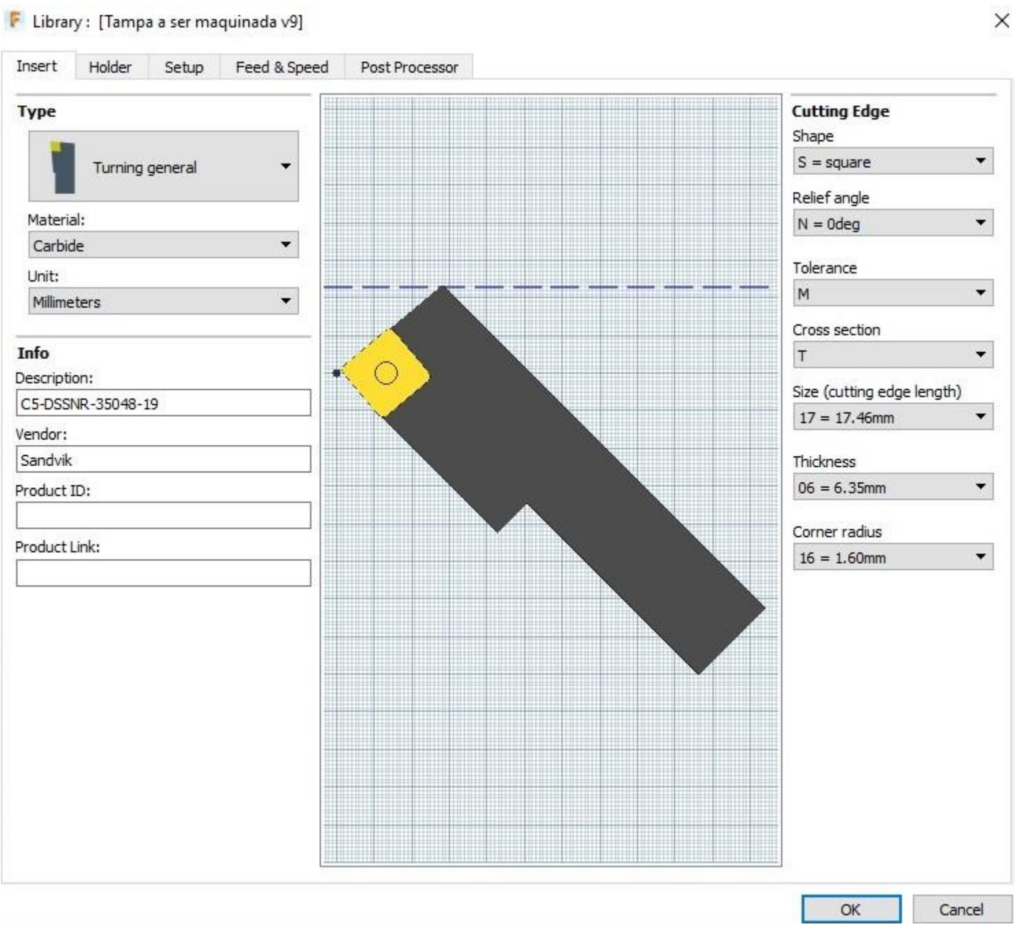


Figure 45 - Add new turning tool menu in Fusion 360

Several characteristics about the tool need to be given: The insert geometry, the holder geometry, the setup (the position on the machine that this tool is on), and the cutting parameters suggested for this tool (it is possible to override the cutting parameters selected here). After those parameters are selected, it is time to define the rest of the operation.

The next two important steps to define the operation are to define the clearance and the number of passes of the operation.

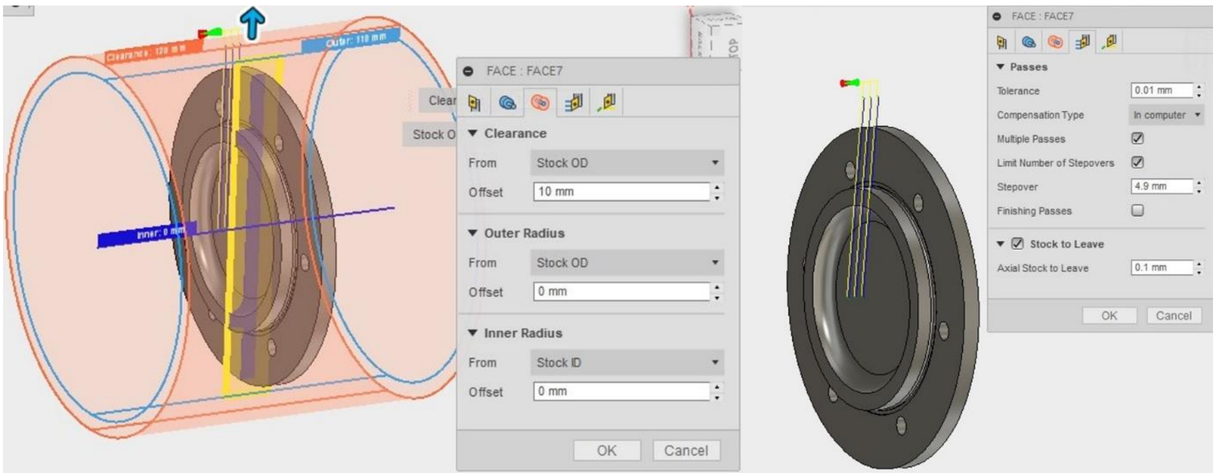


Figure 46 - Clearance and number of passes menus in Fusion 360

The clearance dictates where the tool can operate, and the number of passes defines the depth and types of passes that are to be given in the operation. After this, we should have a defined operation, that can be simulated using the simulate command. The command creates a short video, detailing the visual effect that the operation will create. The menu can be seen below in Figure 47.

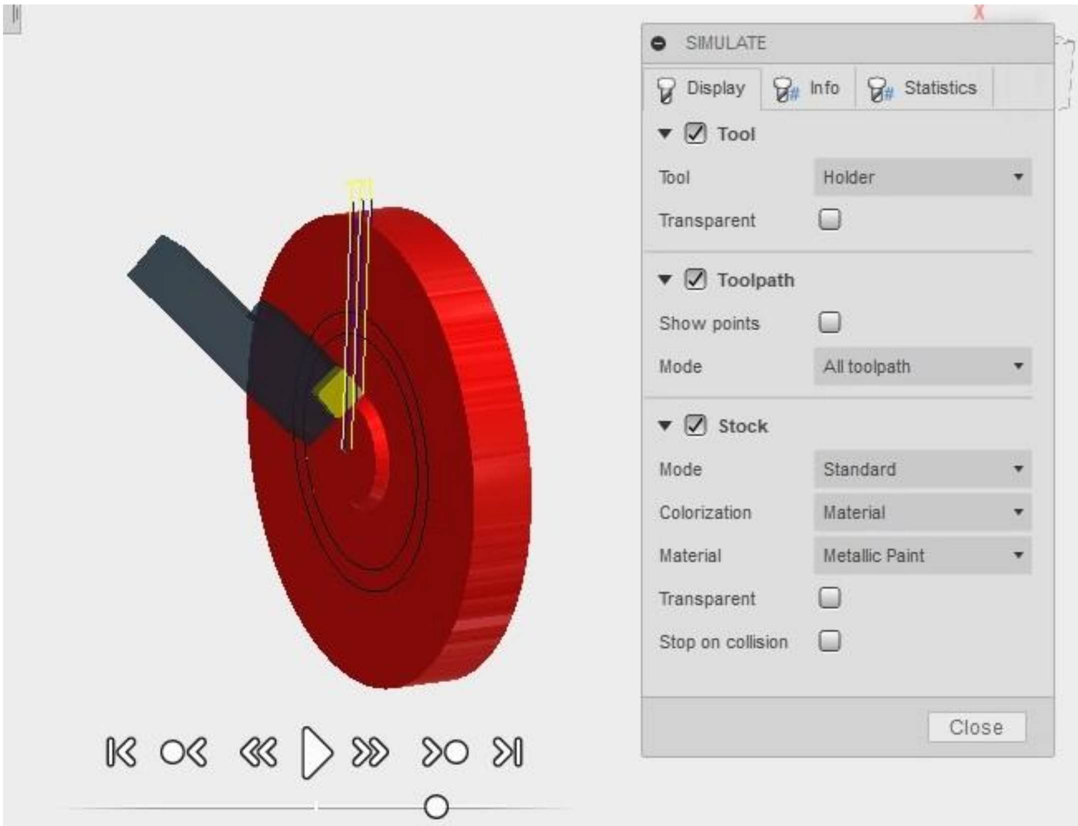


Figure 47 - Simulation menu for CAM operations in Fusion 360

The simulation is useful to calculate the expected machining time and also to visually inspect the programed operation. As a curiosity, I developed a video to represent all the machining operations to obtain this component.

So, all it remains is to prepare the selected machine to manufacture the desired component. In a CNC lathe, it is necessary to:

- Assembling the tools in their correct place.
- Measuring the tool offset of each tool.
- Measuring the workpiece (identify the selected point of origin).
- Run the program and then see if it machines the component to the desired specifications.

And then, the result should be a manufactured component, as it is desired.

8 Conclusions and Future Work

8.1 Conclusions

It was concluded that most of the alterations made to the previous project by João Sousa were not structural, nor functional, but only changes to make the manufacturing processes easier. These alterations, although of primary importance, can be done earlier on the development process, and the only requirement is for the responsible(s) Engineer(s) to have some notions of manufacturing. Thus, this project emphasized how a mixture of both Mechanical design and Manufacturing faculties are required for the formation of competent Design Engineers.

As for the manufacturing, it was noticed that after developing the product from a design point of view, there is still a lot of work to be done before the manufacturing process of the product can be defined. All the components, and sub-components need to have at least one detail drawing, sometimes more, and all of the information needs to be correctly organized to be accessed by the manufacturing teams. The information about the product needs to be precise, and simple to access, to avoid manufacturing errors.

Finally, these kinds of projects gives us the idea that for large scale projects it is usually more productive to have multidisciplinary teams working together, since they are able to achieve better and faster results overall.

8.2 Future Work

Further revisions of this design and manufacturing suggestions can and should be made:

- The Gear design should be studied thoroughly, comparing the machined solution and the welded solution to determine which solution would be better to be mass-produced or produced in small series.
- The housing design should be reviewed. If mass production is the aim, then perhaps a cast iron solution might be a cheaper and better solution.
- Machining sequences for each component should be developed.
- A revision of the manufacturing parameters should be done for each manufacturing process, requiring the consultation of experienced professionals for each one.

From the original Future work that Sousa [5] recommended, those points still need to be developed:

- Dimensioning or selecting the planetary stage gearbox from a manufacturer and selecting the remaining couplings required;
- Thermal analysis of the gearboxes and dimensioning of a circulatory lubrication system capable of supplying both with the required amount of oil for lubrication and heat evacuation;
- Selecting positioning tables capable of supporting, positioning and aligning the components of the powertrain;
- Developing a system capable of supplying the motor with the generators power;
- Connecting the measurement instruments to a data acquisition system;

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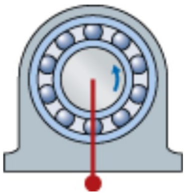
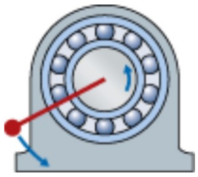
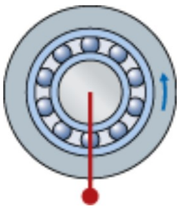
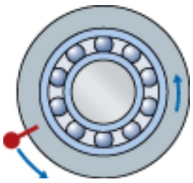
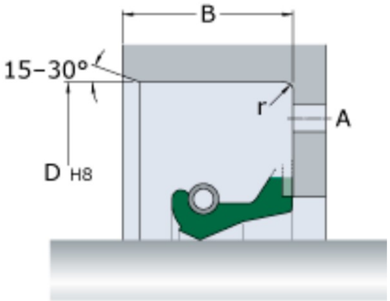
ANNEX A: SKF- Conditions of rotation Table

table 1 - Conditions of rotation

Operating conditions	Schematic illustration	Load condition	Recommended fits
Rotating inner ring Stationary outer ring Constant load direction		Rotating inner ring load Stationary outer ring load	Interference fit for the inner ring Loose fit for the outer ring possible
Rotating inner ring Stationary outer ring Load rotates with the inner ring		Stationary inner ring load Rotating outer ring load	Loose fit for the inner ring possible Interference fit for the outer ring
Stationary inner ring Rotating outer ring Constant load direction		Stationary inner ring load Rotating outer ring load	Loose fit for the inner ring possible Interference fit for the outer ring
Stationary inner ring Rotating outer ring Load rotates with outer ring		Rotating inner ring load Stationary outer ring load	Interference fit for the inner ring Loose fit for the outer ring possible

ANNEX B: SKF- Housing Bore requirements table

table - Housing bore tolerances



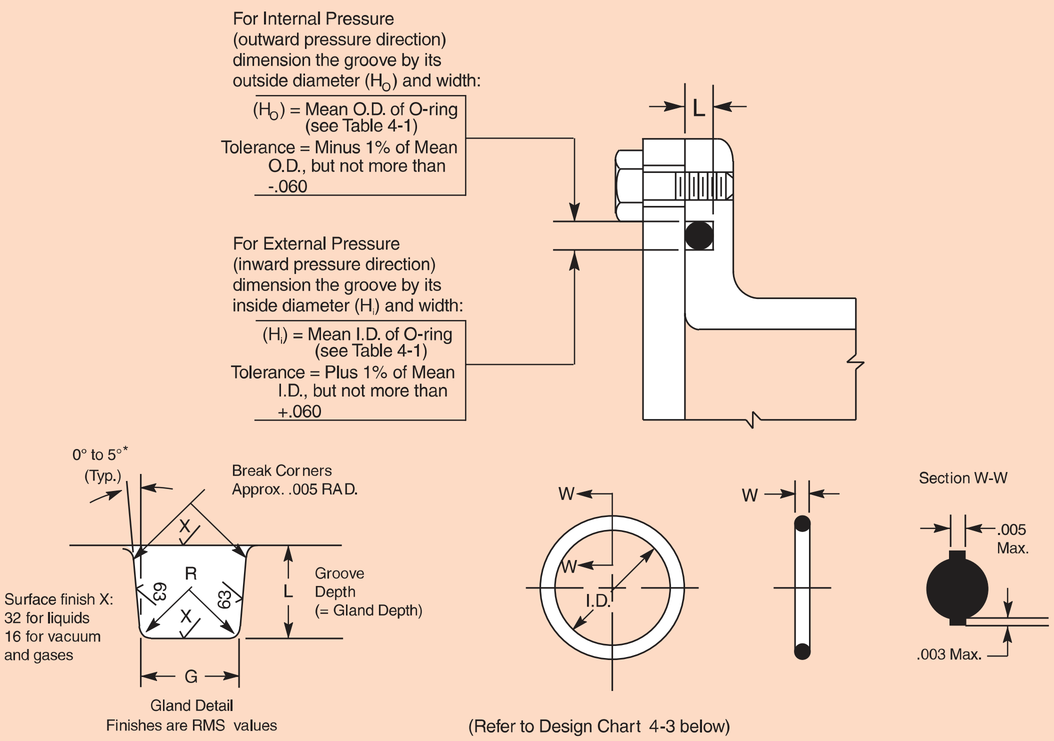
Housing bore for metric seals (ISO)					Housing bore for inch seals (RMA)				
Nominal diameter		**Housing bore** (ISO tolerance H8)		**Fillet radii**	**Nominal diameter**		**Housing bore tolerance**		**Fillet radii**
D					D				r_{max}
over	incl.	high	low	r_{max}	over	incl.	high	low	
mm		µm		mm	in.		in.		in.
	3	+14	0	0,3		**3.000**	+0.001	-0.001	0.031
3	**6**	+18	0	0,3	**3.000**	**7.000**	+0.0015	-0.0015	0.031
6	**10**	+22	0	0,3	**7.000**	**10.000**	+0.002	-0.002	0.031
10	**18**	+27	0	0,3	**10.000**2)	**12.000**	+0.002	-0.002	0.031
18	**30**	+33	0	0,3	**12.000**2)	**20.000**	+0.003	-0.003	0.031
30	**50**	+39	0	0,3	**20.000**2)	**40.000**	+0.004	-0.004	0.031
50	**80**	+46	0	0,4	**40.000**2)	**60.000**	+0.006	-0.006	0.031
80	**120**	+54	0	0,8					
120	**180**	+63	0	0,8					
180	**250**	+72	0	0,8					
250	**315**	+81	0	0,8					
315	**400**	+89	0	0,8					
400	**500**	+97	0	0,8					
500	**630**	+110	0	0,8					
630	**800**	+125	0	0,8					
800	**1 000**	+140	0	0,8					
1 000	**1 250**	+165	0	0,8					
1 250	**1 600**	+195	0	0,8					
1 600	**2 000**	+230	0	0,8					
2 000	**2 500**	+280	0	0,8					
2 500	**3 150**	+330	0	0.8					
3 1501)	**4 000**	+410	0	0.8					
4 0001)	**5 000**	+500	0	0.8					

1) SKF recommended bore specifications not covered in ISO 286-2

2) SKF recommended bore specifications not covered in RMA OS-4

ANNEX C: Parker Static O'ring Housing

Face Seal Glands



(Refer to Design Chart 4-3 below)

O-Ring Face Seal Glands These dimensions are intended primarily for face type O-ring seals and low temperature applications.

O-Ring Size Parker No. 2	W Cross Section Nominal	W Cross Section Actual	L Gland Depth	Squeeze Actual	Squeeze %	G Groove Width Liquids	G Groove Width Vacuum and Gases	R Groove Radius
004 through 050	1/16	.070 ±.003 (1.78 mm)	.050 to .054	.013 to .023	19 to 32	.101 to .107	.084 to .089	.005 to .015
102 through 178	3/32	.103 ±.003 (2.62 mm)	.074 to .080	.020 to .032	20 to 30	.136 to .142	.120 to .125	.005 to .015
201 through 284	1/8	.139 ±.004 (3.53 mm	.101 to .107	.028 to .042	20 to 30	.177 to .187	.158 to .164	.010 to .025
309 through 395	3/16	.210 ±.005 (5.33 mm)	.152 to .162	.043 to .063	21 to 30	.270 to .290	.239 to .244	.020 to .035
425 through 475	1/4	.275 ±.006 (6.99 mm)	.201 to .211	.058 to .080	21 to 29	.342 to .362	.309 to .314	.020 to .035
Special	3/8	.375 ±.007 (9.52 mm)	.276 to .286	.082 to .106	22 to 28	.475 to .485	.419 to .424	.030 to .045
Special	1/2	.500 ±.008 (12.7 mm)	.370 to .380	.112 to .138	22 to 27	.638 to .645	.560 to .565	.030 to .045

Design Chart 4-3: Design Chart for O-Ring Face Seal Glands

Parker Hannifin Corporation • O-Ring Division
2360 Palumbo Drive, Lexington, KY 40509
Phone: (859) 269-2351 • Fax: (859) 335-5128
www.parkerorings.com

ANNEX D: CIN – Protective coatings instructions (Portuguese)

Data de edição: Junho 2013

PROTECÇÃO ANTICORROSIVA DE ESTRUTURAS DE AÇO

1. Introdução

A parte 5 da norma EN ISO 12944 descreve os diferentes tipos de pintura, esquemas mais utilizados na protecção anticorrosiva de estruturas de aço, espessuras recomendadas e número de demãos. Este guia foi criado com base nessas recomendações da referida norma e tem como objectivo orientá-lo na selecção do esquema mais adequado para os diferentes ambientes (ver parte 2 da norma EN ISO 12944), os diferentes graus de preparação de superfície (ver parte 4 da norma EN ISO 12944) e o grau de durabilidade pretendido (ver parte 1 da norma EN ISO 12944).

2. Classificação de ambientes segundo diferentes categorias de corrosividade

Os ambientes são classificados em função do seu grau de corrosividade ambiental, seja para estruturas expostas à corrosividade atmosférica, enterradas ou imersas.
Na tabela 1 são dados alguns exemplos de ambientes para cada tipo de categoria de corrosividade atmosférica e na tabela 2 os agentes corrosivos previstos quando a estrutura de aço se encontra imersa ou enterrada no solo.

Tabela 1: Categorias de corrosividade atmosférica e exemplos de ambientes típicos.

Categoria de corrosividade	Exterior	Interior
C1 **Muito baixa**	-	Edifícios com aquecimento e atmosferas limpas.
C2 **Baixa**	Atmosferas com baixos níveis de contaminação. Áreas rurais.	Edifícios sem aquecimento com possíveis condensações.
C3 **Média**	Atmosferas urbanas e industriais, com moderada contaminação de SO_2. Áreas costeiras com baixa salinidade.	Naves de fabricação com elevada humidade e com alguma contaminação.
C4 **Alta**	Áreas industriais e áreas costeiras com moderada salinidade.	Indústrias químicas, piscinas.
C5-I **Muito alta (industrial)**	Áreas industriais com elevada humidade e com atmosfera agressiva.	Edificados ou áreas com condensações quase permanentes e contaminação elevada.
C5-M **Muito alta (marítima)**	Áreas costeiras e marítimas com elevada salinidade.	Edifícios ou áreas com condensações permanentes e contaminação elevada.

CIN-CORPORAÇÃO INDUSTRIAL DO NORTE, SA
Avenida Dom Mendo, nº831(antes E.N. 13) - Apartado 1008
4471-909 MAIA PORTUGAL
Telef. 22 940 50 00 · Fax: 22 948 56 61
www.cinprotectice.com · email-customerservice.pt

BARNICES VALENTINE, S.A.U.
C/ Riera Seca, 1 – Pol. Ind. Can Milans
08110 – Montcada i Reixac (Barcelona)
Tel. 34 93 565 66 00 · Fax: 34 93 575 33 60
www.cinprotectice.com · email-valentine@valentine.es

CELLIOSE COATINGS
Chemin de la Verriere - BP 58,
69492 Pierre Bénite Cedex · France
Tél: +33 (0) 472 39 77 77 · Fax: +33 (0) 472 39 77 70
www.celiose.com

Todo o território português está classificado segundo estas categorias de corrosividade atmosférica no “Mapa Nacional de Corrosão Atmosférica”.

Tabela 2: Categoria para imersão em água e solo

Categoria de corrosividade	Ambiente	Exemplo de ambientes e estruturas
Im 1	Água doce	Instalações de rio, centrais hidroeléctricas.
Im 2	Água do mar ou salobra	Áreas portuárias com estruturas, tais como portas de comportas, diques, quebra-mares, estruturas de plataformas offshore
Im 3	Solo	Tanques enterrados, condutas e vigas.

3. Classes de durabilidade

A durabilidade ou anos de vida útil, define-se como sendo o tempo a que se deseja chegar até à primeira manutenção por repintura. A durabilidade não é um “tempo de garantia”.

Baixa (L): 2 a 5 anos
Media (M): 5 a 15 anos
Alta (H): > 15 anos.

4. Preparação de Superfície

Antes de se iniciar a decapagem todos os vestígios visíveis de óleo, gordura, sais e outros contaminantes devem ser eliminados, de forma a não ficarem incrustados no aço, nem contaminarem o abrasivo.

Para cada uma das situações o tratamento a executar deverá ser o mais adequado, como por exemplo:

- Para o óleo, gordura ou sais hidrossolúveis, pode-se efectuar uma limpeza com jacto de água (e detergente, se necessário), com vapor, com emulsionantes ou com solventes orgânicos. Sempre que se use detergente, no final passar por água limpa.
- No caso de salpicos de soldadura, sais não hidrossolúveis, cimento, ou outros contaminantes, utilizar ferramentas mecânicas/manuais (por exemplo, escovas, raspadores, etc.).

Os cantos, arestas e cordões de soldadura devem ser arredondados (diâmetro mínimo recomendado é de 2mm), para facilitar a sua pintura.

Após estas operações, decapar por projecção de jacto abrasivo seco todas as superfícies ao grau Sa 2 ½, de acordo com a Norma EN ISO 8501-1. A selecção do abrasivo deve ser feita de forma a garantir um perfil de rugosidade médio entre 25µm e 50µm, determinado com Testex Tape ou mediante o uso de comparadores (G,S) segundo ISO 8503.

CIN-CORPORAÇÃO INDUSTRIAL DO NORTE, SA
Avenida Dom Mendo, nº831(antes E.N. 13) - Apartado 1008
4471-909 MAIA PORTUGAL
Telef. 22 940 50 00 · Fax: 22 948 56 61
www.cinprotectice.com · email-customerservice.pt

BARNICES VALENTINE, S.A.U.
C/ Riera Seca, 1 – Pol. Ind. Can Milans
08110 – Montcada i Reixac (Barcelona)
Tel. 34 93 565 66 00 · Fax: 34 93 575 33 60
www.cinprotectice.com · email-valentine@valentine.es

CELLIOSE COATINGS
Chemin de la Verriere - BP 58,
69492 Pierre Bénite Cedex · France
Tél: +33 (0) 472 39 77 77 · Fax: +33 (0) 472 39 77 70
www.celiose.com

Defeitos do aço revelados após a decapagem (delaminação ou outros) devem ser reparados de maneira apropriada. Se estes tratamentos originarem perda de rugosidade, voltar a decapar estas zonas.

Após a decapagem efectuar a limpeza final, por exemplo, com aspiração potente, deixando a superfície livre de pó e adequadamente limpa para receber o revestimento. Os trabalhos estarão finalizados quando ao aplicar uma fita adesiva sobre a superfície não exista pó aderido à mesma.

Durante o intervalo de tempo que decorre entre a decapagem e a aplicação do revestimento, o grau de preparação das superfícies não poderá sofrer alterações. Assim, por princípio, o tempo máximo entre a decapagem e a aplicação de tinta deverá ser entre 4 e 6 horas, dependendo das condições ambientais.
Sempre que ocorra oxidação da superfície antes da pintura, deve-se voltar a decapar para obtenção do nível de limpeza exigido

Esquemas de pintura

Seguidamente detalhamos alguns esquemas de pintura que cumprem com a Norma ISO 12944 no que diz respeito ao tipo de produto, espessuras e nº de demãos a aplicar. Existem esquemas alternativos, ainda que alguns com produtos não contemplados pela Norma. Para uma melhor informação consulte o Customer Service.
Todos os esquemas aqui apresentados são para uma durabilidade estimada superior a 15 anos.

Categoria de corrosividade C2

Tipo de tinta	Esquema	Espessura seca (micrómetros)
Epoxi Fosfato de Zinco	1 × C-Pox Primer ZP200 HP	80 µm
Acrílico ferro micáceo	1 × C-Cryl S450 Mio	80 µm
	Espessura total	**160 µm**
Epoxi tolerante alumínio	1 × C-Pox ST180 AL	110 µm
Poliuretano	1 × C-Thane S258	50 µm
	Espessura total	**160 µm**

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Avenida Dom Mendo, nº831(antes E.N. 13) - Apartado 1008
4471-909 MAIA PORTUGAL
Telef. 22 940 50 00 · Fax: 22 948 56 61
www.cinprotectice.com · email-customerservice.pt

BARNICES VALENTINE, S.A.U.
C/ Riera Seca, 1 – Pol. Ind. Can Milans
08110 – Montcada i Reixac (Barcelona)
Tel. 34 93 565 66 00 · Fax: 34 93 575 33 60
www.cinprotectice.com · email-valentine@valentine.es

CELLIOSE COATINGS
Chemin de la Verriere - BP 58,
69492 Pierre Bénite Cedex · France
Tél: +33 (0) 472 39 77 77 · Fax: +33 (0) 472 39 77 70
www.celiose.com

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Categoria de corrosividade C3

Tipo de tinta	Esquema	Espessura seca (micrómetros)
Epoxi fosfato de zinco	1 × C-Pox Primer ZP200 HP	100 µm
Poliuretano alta espessura	1 × C-Thane S700 HB	100 µm
	Espessura total	**200 µm**
Epoxi tolerante alumínio	1 × C-Pox ST180 AL	80 µm
Intermédio epoxi	1 × C-Pox S100	80 µm
Poliuretano	1 × C-Thane S258	40 µm
	Espessura total	**200 µm**
Epoxi tolerante de superf.	1 × C-Pox ST160 MP	165 µm
	Espessura total	**165 µm**

Nota: tendo em conta que as espessuras apresentadas para o último esquema aqui apresentado são inferiores às recomendadas na norma EN ISO 12944-5, dispomos de certificados de ensaio segundo a norma EN ISO 12944-6 (ensaio de desempenho), que comprovam que este esquema é válido para esta categoria de corrosividade e durabilidade > 15 anos.

Categoria de corrosividade C4

Tipo de tinta	Esquema	Espessura seca (micrómetros)
Primário etilsilicato de zinco	1 × C-Pox Primer IZS920	75 µm
Intermédio epoxi	1 × C-Pox S130 FD	125 µm
Poliuretano	1 × C-Thane RPS HS	50 µm
	Espessura total	**250 µm**
Primário rico em zinco	1 × C-Pox Primer ZN650	50 µm
Epoxi tolerante de superf.	1 × C-Pox ST160 MP	100 µm
	Espessura total	**150 µm**

Nota: tendo em conta que as espessuras apresentadas para o último esquema aqui apresentado são inferiores às recomendadas na norma EN ISO 12944-5, dispomos de certificados de ensaio segundo a norma EN ISO 12944-6 (ensaio de desempenho), que comprovam que este esquema é válido para esta categoria de corrosividade e durabilidade > 15 anos. Dispomos ainda de certificado de ensaio para o primeiro esquema.

Categoria de corrosividade C5M

Tipo de tinta	Esquema	Espessura seca (micrómetros)
Primário rico em zinco	1 × C-Pox Primer ZN800	75 µm
Intermédio epoxi	1 × C-Pox S990 Mio FD	85 µm
Poliuretano	2 × C-Thane RPS HS	80 µm
	Espessura total	**240 µm**

Nota: tendo em conta que as espessuras apresentadas são inferiores às recomendadas na norma EN ISO 12944-5, dispomos de certificados de ensaio segundo a norma EN ISO 12944-6 (ensaio de desempenho), que comprovam que este esquema é válido para esta categoria de corrosividade e durabilidade > 15 anos.

CIN-CORPORAÇÃO INDUSTRIAL DO NORTE, SA
Avenida Dom Mendo, nº831(antes E.N. 13) - Apartado 1008
4471-909 MAIA PORTUGAL
Telef. 22 940 50 00 · Fax: 22 948 56 61
www.cinprotectice.com · email-customerservice.pt

BARNICES VALENTINE, S.A.U.
C/ Riera Seca, 1 – Pol. Ind. Can Milans
08110 – Montcada i Reixac (Barcelona)
Tel. 34 93 565 66 00 · Fax: 34 93 575 33 60
www.cinprotectice.com · email-valentine@valentine.es

CELLIOSE COATINGS
Chemin de la Verriere - BP 58,
69492 Pierre Bénite Cedex · France
Tél: +33 (0) 472 39 77 77 · Fax: +33 (0) 472 39 77 70
www.celiose.com

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Categoria de corrosividade C5M (cont.)

Tipo de tinta	Esquema	Espessura seca (micrómetros)
Primário epoxi fosf. zinco	1 × C-Pox Primer ZP200 HB	100 μm
Intermédio epoxi ferro micáceo	1 × C-Pox S990 Mio FD	140 μm
Poliuretano	2 × C-Thane RPS HS	80 μm
	Espessura total	**320 μm**
Primário epoxi zinco	1 × C-Pox Primer ZP650	75 μm
Poliuretano flexíbel de alta espessura	1 × C-Thane S690 HB-F	125 μm
	Espessura total	**200 μm**

Nota: tendo em conta que as espessuras apresentadas para o último esquema aqui apresentado são inferiores às recomendadas na norma EN ISO 12944-5, dispomos de certificados de ensaio segundo a norma EN ISO 12944-6 (ensaio de desempenho), que comprovam que este esquema é válido para esta categoria de corrosividade e durabilidade > 15 anos. Dispomos ainda de certificado de ensaio para o primeiro esquema.

Categoria de corrosividade Im1, Im2 e Im3

Tipo de tinta	Esquema	Espessura seca (micrómetros)
Primário epoxi rico em zinco	1 × C-Pox Primer ZN905	60 μm
Epoxi Tolerante de superfície	2 × C-Pox ST165 MP-WN	400 μm
	Espessura total	**460 μm**
Epoxi de alcatrão	2 × C-Pox CT940	400 μm
	Espessura total	**400 μm**

A CIN dispõe de muitos outros esquemas para a protecção anticorrosiva de estruturas metálicas. Para mais informações contactar o Customer Service da CIN.

CIN-CORPORAÇÃO INDUSTRIAL DO NORTE, SA
Avenida Dom Mendo, nº831(antes E.N. 13) - Apartado 1008
4471-909 MAIA PORTUGAL
Telef. 22 940 50 00 · Fax: 22 948 56 61
www.cinprotectice.com · email-customerservice.pt

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C/ Riera Seca, 1 – Pol. Ind. Can Milans
08110 – Montcada i Reixac (Barcelona)
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www.cinprotectice.com · email-valentine@valentine.es

CELLIOSE COATINGS
Chemin de la Verriere - BP 58,
69492 Pierre Bénite Cedex · France
Tél: +33 (0) 472 39 77 77 · Fax: +33 (0) 472 39 77 70
www.celiose.com

ANNEX E: International – Protective coatings instructions

International

ISO 12944

Protect your assets in three easy steps

AkzoNobel

Select your ISO 12944 compliant system in 3 easy steps

Step 1
Select the corrosive environment

Use the following table to select the most appropriate classification for your project:

ISO 12944 CLASSIFICATION	TYPICAL ENVIRONMENTS
C1 C2	Heated buildings/neutral atmosphere Rural areas, low pollution
C3	Urban and industrial atmospheres Moderate sulfur dioxide levels Production areas with high humidity
C4	Industrial and coastal Chemical processing plants
C5I	Industrial areas with high humidity and aggressive atmospheres
C5M	Marine, offshore*, estuaries, coastal areas with high salinity

* Corrosion protection in ISO 12944 C5M - Offshore environments is being addressed via a new standard (ISO 20340) dedicated to this environment

These environments are based on experiments that have measured the rate of metal loss for uncoated steel. The classification of environments applies to structural steel exposed to ambient (less than 120°C [248°F]) conditions.

Many city locations could be classified as ISO 12944 C3

Step 2
How long until first major maintenance?

Use the following table to select how durable you want your coating system to be. The higher the durability, the longer the time to first major maintenance:

High Durability	>15 years to first major maintenance
Medium Durability	5-15 years to first major maintenance
Low Durability	<5 years to first major maintenance

Remember, when selecting the most cost effective system for your project, durability does not equate to a guarantee time. Durability relates to the performance duration of the coating system before first major maintenance. Regular minor maintenance should always be anticipated in order to achieve the required life to first major maintenance.

C5M Marine environments present the toughest conditions and require more durable systems

Why is ISO 12944 so important?

ISO 12944 Paints & Varnishes - Corrosion protection of steel structures by protective paint systems (parts 1-8) (1998).

The ISO 12944 standard is intended to assist engineers and corrosion experts in adopting best practice in corrosion protection of structural steel at new construction.

ISO 12944 is progressively superseding regional standards to become a truly global benchmark in corrosion control.

Selecting specifications that comply with ISO 12944 provides you with:

- Confidence that the corrosion protection you specify will be fit for purpose
- An objective approach to coating selection
- A simplified matrix of coating systems to select from
- A meaningful coating design life
- A universally accepted standard

Understanding your ISO environment can help to tailor specifications, ensuring your coatings are not under or over specified and saving you unnecessary cost.

Regular inspection and routine maintenance via our Interplan™ service will assist in achieving the required design life for the coating system

Step 3
Select your ISO 12944 compliant system

The coating systems described in this brochure have been evaluated against ISO and ASTM test standards and self certified to ISO 12944 part 6.

ISO 12944 ENVIRONMENT	DESIGN LIFE/DURABILITY <5 YEARS	DESIGN LIFE/DURABILITY 5-15 YEARS	DESIGN LIFE/DURABILITY >15 YEARS
C1	A	A	A
C2	A	A	B
C3	B or C	B or C	D, E or F
C4	#	G or H	G or H
C5I and C5M	#	I or J	I or J

We do not routinely recommend systems for Design Lives <5 years in C4 or C5 environments

REFERENCE	COATING SYSTEM	DFT	CONTAINS FREE ISOCYANATE (1)	SYSTEM VOC	AESTHETIC DURABILITY (2)	CORROSION RESISTANCE (3)
A	Interlac® 665 or Intergard® 345	@ 80µm (3.1 mils)	No	<40g/m^2	★	★
B	Intergard® 345 (4)	@ 160µm (6.3 mils)	No	<73g/m^2	★	★★
C	Intercure® 99 (5)	@ 160µm (6.3 mils)	Yes	<40g/m^2	★★★★	★★½
D	Intercure® 99 (6)	@ 200µm (8 mils)	Yes	<50g/m^2	★★★★	★★★
E	Intercure® 200HS Interthane® 990 (7)	@ 150µm (6 mils) @ 50µm (2 mils)	Yes (6)	<80g/m^2	★★★ (8)	★★★
F	Intercure® 200HS Interfine® 878	@ 150µm (6 mils) @ 50µm (2 mils)	No	<60g/m^2	★★★★★	★★★
G	Intercure® 200HS Interfine® 878	@ 205µm (8 mils) @ 75µm (3 mils)	No	<85/m^2	★★★★★	★★★½
H	Interzinc® 52 Intergard® 475HS Interthane® 990 (7)	@ 75µm (3 mils) @ 155µm (6.1 mils) @ 50µm (2 mils)	Yes	<112g/m^2	★★★ (8)	★★★★
I	Interzinc® 52 Intergard® 475HS Interthane® 990 (7)	@ 75µm (3 mils) @ 200µm (8 mils) @ 50µm (2 mils)	Yes	<126g/m^2	★★★ (8)	★★★★★
J	Interzinc® 52 Intergard® 475HS Interfine® 878	@ 75µm (3 mils) @ 200µm (8 mils) @ 60µm (2.4 mils)	No	<100g/m^2	★★★★★	★★★★★

(1) Coatings containing isocyanate have known health and safety issues during application. Many of our products contain no free isocyanate.

(2) Aesthetic durability is a measure of gloss and color retention. These results are based on ISO and ASTM testing carried out in an ISO 9001 certified laboratory.

(3) Corrosion resistance is a measure of the anticorrosive performance. These results are based on ISO and ASTM testing carried out in an ISO 9001 certified laboratory.

(4) Durability (gloss and color retention) when exposed to sunlight can be significantly improved by topcoating this specification with Interthane® 990 @ 50µm (2 mils). In these instances it is possible to reduce the thickness of Intergard® 345 from 160µm (6.3 mils) to 100 - 125µm (4 - 5 mils).

(5) Fast dry in 1½ hours at 25°C (77ºF) Intercure® 99 will reduce (VOC) emissions, improve productivity and increase aesthetic durability compared to Intergard® 345.

(6) Intercure® 99 can be a direct replacement for two coat systems in C3 environments. Fewer coats means improved productivity and Intercure® 99 dries fast in 1½ hours at 25°C (77ºF), has excellent aesthetic durability and can reduce the overall VOC emissions of your system.

(7) Interthane® 990 is a high gloss finish - if a semi-gloss finish is required it can be replaced by Interthane® 870 specified at 100µm (4 mils). In this instance the previous coat can be reduced by 50µm (2 mils) in order to achieve the same total dry film thickness (DFT).

(8) As Interfine® 878 contains no free isocyanate, replacing Interthane® 990 with Interfine® 878 will reduce health and safety concerns and will also increase aesthetic durability to 5★.

You can have confidence in our coatings

- Continual investment in state of the art R&D and test facilities
- Testing to industry standards including NACE, ASTM, ISO, NORSOK, NSF and more
- Customized testing to meet specific customer and project needs
- Extensive in-house test data
- Independent testing and approvals
- In-field testing and proof of performance track record

Sustainability

Here at AkzoNobel, we are committed to sustainability and are ranked number one on the influential Dow Jones Sustainability Index (DJSI), demonstrating our commitment to improving our environmental and social performance.

We will work with you to help ensure that your coating specification will meet your overall sustainable design credentials.

Global organization

As your global partner we provide consistent solutions, time and time again.

Designing assets, fabricating and constructing in numerous locations across the world? Combining worldwide manufacturing and local distribution networks with our global product range helps to reduce the complexity in specification and the variance in quality. From us, this means one product, one datasheet regardless of location.

We supply consistent products and consistent service, whenever and wherever you need it. From three global state of the art R&D facilities in the UK, USA and China, we are developing the coatings of tomorrow for your business. Our design and development, marketing, technical and commercial support are accredited to ISO 9001 which means you can have absolute confidence in our products and services.

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G4_12944_UK
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ANNEX F: OK AristoRod 12.62 – Product sheet

OK AristoRod 12.62

GMAW
ER70S-2

Description

OK AristoRod™ 12.62 is a bare triple desoxidised G2Ti/ER70S-2 solid wire for the GMAW of non-alloyed steels, as used in general construction, pressure vessel fabrication and shipbuilding. It yields high-quality welds in semi-killed and rimmed steels, as well as with grades with various carbon contents. Added desoxidants, Al - Ti- Zr, make the wire also suitable for steels with a dirty or rusty surface, without sacrificing weld quality.

OK AristoRod 12.62 is treated with ESAB's unique Advanced Surface Characteristics (ASC) technology, taking MAG welding operations to new levels of performance and all-round efficiency, especially in robotic and mechanised welding. Characteristic features include excellent start properties; trouble-free feeding at high wire speeds and lengthy feed distances; a very stable arc at high welding currents; extremely low levels of spatter; low fume emission; reduced contact tip wear and improved protection against corrosion of the wire.

Welding current

DC+

Classifications

SFA/AWS A5.18	ER70S-2
EN 440	G2Ti

Wire composition

C	Si	Mn
0.06	0.6	1.2

Typical mech. properties all weld metal

Yield stress, MPa	>380
Tensile strength, MPa	470-600
Elongation, %	>20

Charpy V

Test temps, °C	Impact values, J
-30	>47

Welding parameters

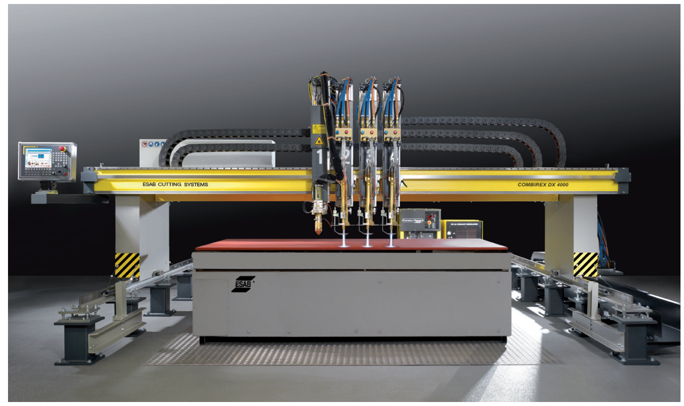
Diameter, mm	Wire feed, m/min	Welding current, A	Arc voltage, V	Deposition rate kg weld metal/hour
0.9	3.0-12.0	70-250	18-26	0.8-3.3
1.0	2.7-15.0	80-300	18-32	1.0-5.5
1.2	2.5-15.0	120-380	18-35	1.3-8.0

ANNEX G: Combirex DX – Product specifications

Combirex™ DX

CNC Gantry Cutting Machine

The Combirex DX offers large gantry design and performance in a compact package. The rugged gantry features all-steel construction with machined mating surfaces for stiffness and accuracy. Heavy duty H-beam weldments support triple machined T-rails to provide a sturdy, stable foundation, and easy installation on any concrete floor. Featuring a precision linear rail Y-axis guiding system, precision three-axis rack-and-pinion drives, digital AC drives and AC brushless motors, this machine delivers the cutting performance you would expect from much more expensive gantries.



Gantry Specifications

Combirex DX	2500	3000	3500	4000
Recommended Max. Plate Width	5' (1.5 m)	6' (2 m)	8' (2.4 m)	10' (3 m)
Maximum Cross Travel with 1 Tool	78.74" (2000 mm)	98.43" (2500 mm)	118.11" (3000 mm)	137.80" (3500 mm)
Maximum Cross Travel with 2 Tools	78.74" (2000 mm)	98.43" (2500 mm)	118.11" (3000 mm)	137.80" (3500 mm)
Maximum Cross Travel with 3 Tools	70.87" (1800 mm)	90.55" (2300 mm)	110.24" (2800 mm)	129.92" (3300 mm)
Maximum Cross Travel with 4 Tools	62.99" (1600 mm)	82.68" (2100 mm)	102.36" (2600 mm)	122.05" (3100 mm)
Rail Gauge	98.4" (2500 mm)	118.1" (3000 mm)	137.8" (3500 mm)	157.5" (4000 mm)
Internal Clearance	86" (2184 mm)	106" (2692 mm)	126" (3200 mm)	145" (3683 mm)
Maximum Table Outside Width	77" (1956 mm)	96.5" (2451 mm)	116" (2947 mm)	136" (3454 mm)
Machine Width	142.7" (3625 mm)	162.4" (4125 mm)	182.1" (4625 mm)	201.8" (5125 mm)
Machine Height	83" (2100 mm)			
Work Table Height	26" - 30" (660 - 762 mm)			
Parking Area	56" (1463 mm)			
Speed Range	2 - 1,000 ipm (50.8 - 25000 mm/min)			
Power Requirement	230/460/575 VAC, 50/60 Hz, Single-Phase, 30 Amp (Special input voltages are available upon request)			

Rail System Specifications

Track Height 18.23" (463 mm)

Rail Length	Travel Length	H-Beam Length
5 m	11' - 8" (3569 mm)	206" (5236 mm)
6 m	14' - 11" (4569 mm)	246" (6236 mm)
8 m	21' - 6" (6569 mm)	324" (8236 mm)
9 m	24' - 9" (7569 mm)	364" (9236 mm)
10 m	28' - 1" (8569 mm)	403" (10236 mm)
12 m	34' - 8" (10569 mm)	482" (12236 mm)
15 m	44' - 6" (13569 mm)	600" (15236 mm)
20 m	60' - 11" (18569 mm)	797" (20236 mm)

Tool Specifications

Cutting Processes	Plasma, Oxy-Fuel
Plasma System Options	Up to 450 Amps
Plasma Cutting Thickness	max. 2.5 inch, depending on plasma unit
Maximum Plasma Stations	1
Oxy-Fuel Cutting Thickness	max. 8 inch (edge start)
Maximum Pierce Thickness	6 inch (with one oxy-fuel torch)
Maximum Oxy-Fuel Stations	4
Maximum Marking Tools	1 Air-Scribe Unit
Maximum Total Stations	4
Maximum Tool Configurations	1 plasma and 3 oxy-fuel, or 4 oxy-fuel, or 1 plasma, 1 marker, and 2 oxy-fuel

Standard Features

- **3 Axis Gantry with Rack-and-Pinion Drives**
- **Reinforced Box Beam Design Provides a Solid, Precision Platform For the Cutting Tool**
- **Precision Linear Rail Y-Axis Guide Way For Greater Accuracy**
- **Trucks are Machined and Welded, with Oversized Wheel Bearings for Increased Stability and Accuracy**
- **Machined Mating Surfaces for high stiffness and accuracy**
- **ESAB's Vision CNC, Windows® based, Networkable, with Color LCD**
- **Digital AC Drive Amplifiers for years of maintenance free operation**
- **AC Brushless Motors for wide speed range with accurate speed control**
- **Precision Heavy-Duty Gearboxes for accuracy and smooth motion**
- **Maximum Machine Speed: 1000 ipm (25000 mm/min)**
- **Cross Axis Powertrack Hose & Cable Carriers**
- **Suitable for material up to 6" thick (150 mm) standard.**
- **Positioning Accuracy: +/- .010", Repeatability: +/- .005"**
- **Precision drive rack mounted directly to machined surface for precise rack alignment**
- **Heavy Duty H-Beam Rail Supports**
- **Triple Machined T-Rail System for Accuracy and Durability**

Specifications are subject to change without notice. Please contact ESAB Cutting Systems for the most current specifications, numerical control, and available equipment.

Plasma Stations

The Combirex DX can be equipped with air plasma systems up 100 amps or ESAB's m3 Precision Plasmarc System, which allows the machine to cut and mark with the same plasma torch. The m3 system is available on the Combirex DX in 200 Amp, 360 Amp, and 450 Amp configurations.

The plasma station includes a pneumatically balanced initial height sensor along with an electrical clear-the-plate feature, for the softest, most accurate tool-tip initial height sensing. Arc Voltage Height Control provides accurate cutting height and a magnetic break-away crash protection system prevents torch damage in case of tipped parts. The heavy duty torch lifter features a linear rail for stability and provides 8" (200 mm) of vertical stroke.

Oxy-Fuel Torch Stations

The Combirex DX may be equipped with up to 4 oxy-fuel cutting stations. The stations feature heavy duty motorized lifters with capacitive height control and pilot flame torch ignitors. An electronic proportional valve gas control sets high/low preheat pressures, cutting oxygen pressure, and pierce ramp automatically through the built-in process database.

Plate Marking

With the Combirex DX, plate marking can be accomplished by the m3 plasma system or by an optional air scribe marker, allowing accurate marking and cutting on the same parts.

Additional Options

The following tool and machine options are available on the Combirex DX:

- Air Curtain for under-water plasma cutting
- Laser Pointer for manual plate alignment
- Down draft or water cutting tables
- Columbus™ programming software

ESAB Cutting Systems

U.S.A.
411 S. Ebenezer Rd.
Florence, SC 29501
Phone: 843-664-4394

Canada
6010 Tomken Road
Mississauga, Ontario L5T 1X9
Phone: 905-670-0220

Mexico
AVE. Diego Diaz de Berlanga No. 130
Col. Nogalar
San Nicolas de los Garza, N.L. 66480
Monterrey, Mexico
Phone: 81-8305-3700

Web: www.esab-cutting.com
E-Mail: us.mgr.cutting@esab.com

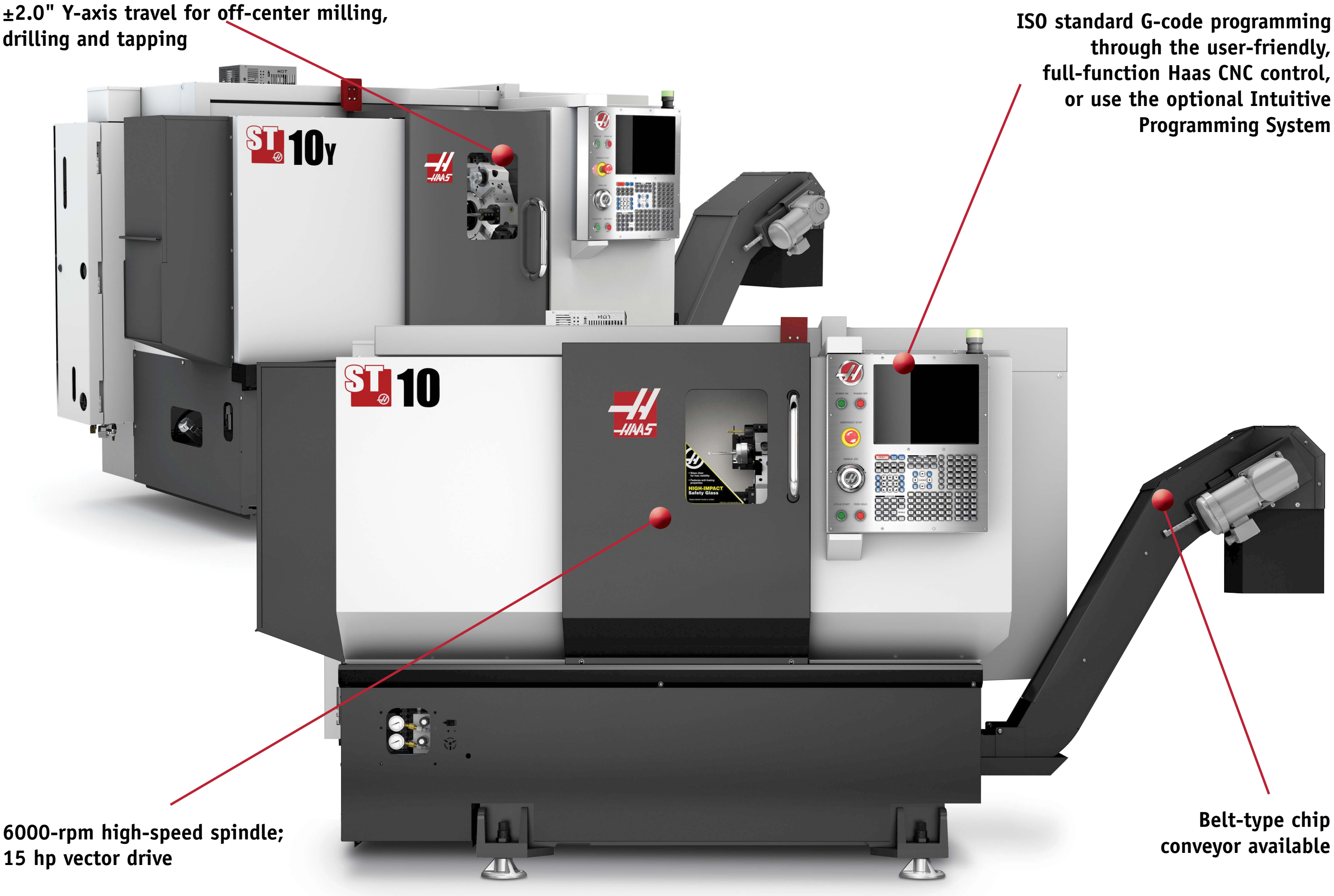
MCUT-3027 2013-01-15

ANNEX H: HAAS ST-10 - Product specifications

[Special Series]

Haas ST-10 Series Lathes

The High-Performance Turning Centers



Warranty: 1 Year Parts and Labor

[Standard Features]

- 6.5" Hydraulic Chucking System
- 6000-rpm Spindle
- 15 hp Vector Drive
- A2-5 Spindle Nose
- 1.75" Bar Capacity
- 15" Color LCD Monitor w/USB Port
- 1 MB Program Memory
- Rigid Tapping
- Made in the USA

[ST-10]

- 14" x 16" Max Capacity
- 12-Station BOT Turret
- 1200 ipm Rapids

[ST-10Y]

- 12" x 16" Max Capacity
- ±2.0" Y-Axis Travel
- 6000-rpm Live Tooling with C Axis
- 12-Station Hybrid BOT/VDI Turret
- 1200 ipm Z-Axis Rapids

[Options] partial list

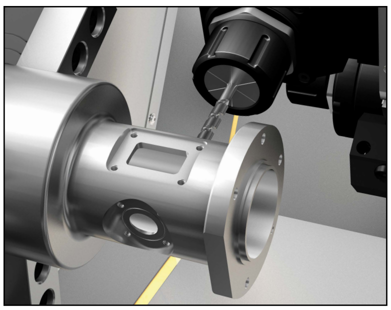
- Tailstock with Hydraulic Quill
- High-Pressure Coolant Systems
- Automatic Tool Presetter System
- Automatic Parts Catcher System
- Belt-Type Chip Conveyor
- Ethernet Interface
- Haas Intuitive Programming System
- Haas Bar Feeder
- Auto Door

Haas ST-10 Series Lathes

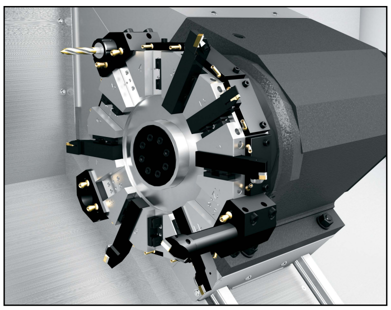
The High-Performance Turning Centers

The ST-10 has a small footprint, yet provides a maximum capacity of 14" x 16", with a maximum part swing of 16.5". The spindle turns to 6000 rpm, and the 15 hp vector drive system provides 75 ft-lb of cutting torque. A 6.5" hydraulic chucking system and 12-station turret are standard.

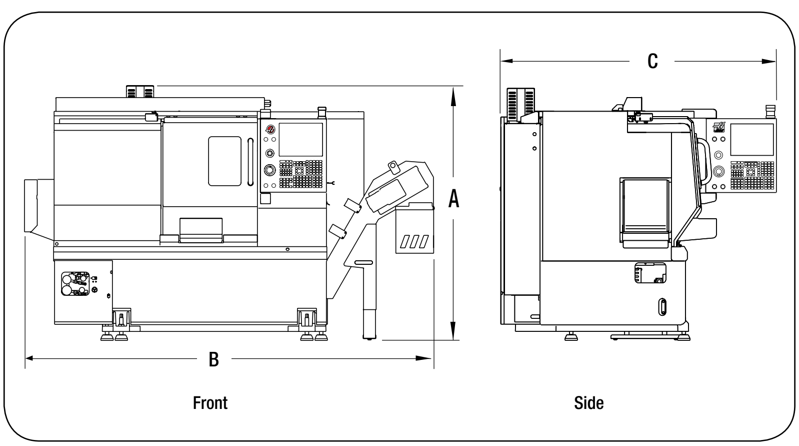
The ST-10Y adds 4" of Y-axis travel (±2" from the centerline) for off-center milling, drilling, and tapping, and comes standard with 6000-rpm live tooling and a C axis for versatile 4-axis capability.



The ST-10Y's generous Y-axis travel, high-speed live tooling, and C-axis motion allow multiple operations in a single setup to reduce part handling and increase accuracy.



Both ST-10 models are equipped with a 12-station turret (BOT or hybrid BOT/VDI) that indexes quickly to reduce cycle times.



Operating Dimensions	ST-10/ST-10Y
A. Max Operating Height	73" 1 854 mm
B. Max Operating Width	126" 3 200 mm
C. Max Operating Depth†	73" 1 854 mm

† With control swung forward. Additional 36" (914 mm) required to open rear service panel.

[Specifications]

Capacities	ST-10	ST-10Y
Chuck Size	6.5" 165 mm	6.5" 165 mm
Max Cutting Dia.	14" [1] 356 mm	12" 305 mm
Max Cutting Length without workholding	16" 406 mm	16" 406 mm
Std. Bar Capacity	1.75" 44 mm	1.75" 44 mm
Spindle		
Max Speed	6000 rpm	6000 rpm
Max Motor Rating	15 hp 11.2 kW	15 hp 11.2 kW
Max Torque	75 ft-lb @ 1300 rpm 102 Nm @ 1300 rpm	75 ft-lb @ 1300 rpm 102 Nm @ 1300 rpm
Spindle Nose	A2-5	A2-5
Spindle Bore	Ø2.31" Ø58.7 mm	Ø2.31" Ø58.7 mm
Swing Diameter		
Max Part Diameter	16.5" 419 mm	16.5" [2] 419mm
Swing Over Wedge	16.5" 419 mm	16.5" [2] 419 mm
Travels & Feedrates		
X Axis	7.88" 200 mm	7.88" 200 mm
Y Axis	— —	±2.0" ±51 mm
Z Axis	16" 406 mm	16" 406 mm
X-Axis Rapids	1200 ipm 30.5 m/min	472 ipm 12 m/min
Y-Axis Rapids	— —	472 ipm 12 m/min
Z-Axis Rapids	1200 ipm 30.5 m/min	1200 ipm 30.5 m/min
General		
Power – 3-Phase	195 - 260 V	195 - 260 V

[1] Max diameter with standard BOT turret; VB = 12" (305 mm); VDI=9.0" (229 mm).
[2] With Y axis at 0.

ANNEX I: ETR01Co02 - Machining Sequence

Supplied in an external volume.

ANNEX J: Manufacturing Sheets

Supplied manufacturing sheets in this volume:

- ETR01Co02
- ETR01Ge3
- ETR01AA1
- ETR01AA2P01

Assembly code: ETR01

Sub Assembly code: ---

Part nº: 34 – IShaft Cover

Part Code: Co02

Suggested material:
Ramada C1/ DIN 9 SMn 36 K/28 K

Manufacturing processes applicable:

1- **Plasma cut:**
   a. Suggested Machine: ESAB Combirex DX
   b. Sheet thickness: 40 mm

2- **Machining**
   a. Initial Block: Ø220x40 mm
   b. Final total mass: 2.8 kg
   c. Suggested Machine 1: HAAS ST-10 (live tooling required)
      i. Selected Tools:
         1. Tool: Sandvik C5-DSSNR-35048-19
            a. Insert: Sandvik SNMG 19 06 16-PR 4335
         2. Tool: Sandvik DCKNR 2020K 12
            a. Insert: Sandvik CNMG 12 04 08-XF 4325
         3. Tool: Sandvik C5-DSRNR-27060-19
            a. Insert: Sandvik SNMG 19 06 16-PR 4325
         4. Tool: Sandvik TR-V13JBR 2020K
            a. Insert: Sandvik TR-VB1312-F 4325
         5. Hoffmann 2032112 Ø2mm
         6. Tool: Sandvik 880-D2000L25-02
            a. Insert peripheral: Sandvik 880-04 03 W07H-P-GR 4334
            b. Insert Central: 880-04 03 05H-C-GR 1044
         7. Tool: Sandvik A16R-SSKCR 09-R
            a. Insert: Sandvik SCMT 09 T3 12-PR 4325
         8. Tool: Sandvik TR-SL-V13LBR-25
            a. Insert: Sandvik TR-VB1312-F 4325
         9. Tool: Sandvik C5-DSDNN-00065-19
            a. Insert: Sandvik SNMG 19 06 16-PR 4325
         10. Sandvik Corodrill 860.1-1110-037A1-PM 4234
   d. Machining sequence available

3- **Surface Finishing**
   a. Total surface area: 0.07717 m2
   b. Sand Blasting grade: Sa 1/2
      i. Surface roughness: 25 to 50 μm
   c. Corrosivity category chosen: C5M
      i. Primer: 1x C-POX Primer ZN800 (75 μm)

ii. Intermediate: 1x C-POX S990 Mio FD (85 μm)
iii. Top Coat: 2x C-Thane RPS HS (80 μm)
iv. Total Thickness: 240 μm

Technical drawing codes: PT000028

Assembly code: ETR01

Sub Assembly code: ---

Part nº: 49 – Gear Z3

Part Code: Ge3

Suggested material:
G15 Special Ramada/ DIN 17 CrNiMo 6

Manufacturing processes applicable:

1- **Oxy-fuel cut:**
    a. Suggested Machine: ESAB Combirex DX
    b. Sheet thickness: 220 mm
2- **Machining**
    a. Initial Block Ø260x220 mm
    b. Final total mass: 33.1 kg
    c. Suggested Machine 1: Haas ST-30Y (live tooling required)
        i. Tools:
    d. Suggested Machine 2: Ohio Broach RP/224
        i. Tools:
    e. Machining sequence nº:
3- **Finishing teeth grinding (Fine grit)**
    a. Number of teeth: 27
    b. Module: 8.0 mm
    c. Tip Relief
        i. Height: 7.09 mm
        ii. Coefficient: 90 μm
    d. Surface Roughness expected: Ra 0.6 μm
4- **Heat Treatment**
    a. Superficial Carburizing
        i. Required Temperature: 880 - 940ºC
        ii. Suggested Procedure: Induction Heating
    b. Post-Carburizing Tempering
        i. Temperature: 150-200ºC

Technical drawing codes: PT000050

Assembly code: ETR01

Part Code:

Sub Assembly code: AA1

Suggested material: DIN St52-3 U

Part nº: 5 – Housing sub-assembly

Manufacturing processes applicable:

1- Welding

a. Welding type: MAG
b. Suggested Welding consumable: ESAB OK AristoRod 12.62
c. Suggested Parameters:

Diameter, mm	Wire feed, mm/min	Welding Current, A	Arc Voltage, V	Deposition rate kg/hour
1.2	2.5-15	120-380	18-35	1.3-8.0

d. Welding process sheets

2- Machining

a. Initial Block: Welded assembly result
b. Final total approximate mass: 1309 kg
c. Suggested Machine 1: HAAS EC 1600
    i. Tools:
d. Machining sequence nº:

3- Surface Finishing

a. Total surface area: 11.0347 m2
b. Sand Blasting grade: Sa 1/2
    i. Surface roughness: 25 to 50 μm
c. Corrosivity category chosen: C5M
    i. Primer: 1x C-POX Primer ZN800 (75 μm)
    ii. Intermediate: 1x C-POX S990 Mio FD (85 μm)
    iii. Top Coat: 2x C-Thane RPS HS (80 μm)
    iv. Total Thickness: 240 μm

Technical drawing codes: PT000006; PT000005; PT000004; PT000003.

Assembly code: ETR01

Part Code: P01

Sub Assembly code: AA2

Suggested material: DIN St52-3 U

Part nº: 16 – Housing Cover; 1

Manufacturing processes applicable:

1- **Plasma cut:**
    a. Suggested Machine: ESAB Combirex DX
    b. Sheet thickness: 5 mm
2- **Sheet metal Bending**
    a. Suggested Machine: Guimadira PM 13530
        i. Bending angle 1: 150º
        ii. Bending angle 2: 150º
    b. Sheet Thickness: 5 mm
    c. Suggested Tool: Rolleri Tools 01630 / Die: Rolleri Tools M60.85.32

Technical drawing codes: PT000020; PT000021.