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DESIGN OF A TEST RIG FOR A NOVEL JOINING METHOD

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ABSTRACT

This paper presents the development of an experimental setup in order to study a novel assembly method based on knurling. The assembly method is used as an alternative to the ordinary lathing process. The idea arises from the necessity of finding a new method of manufacturing work-pieces which would not generate turnings during the process, as well as having the possibility of hollowing the work-piece in order to reduce its weight and save costs.

The resultant design is a combination of electro-mechanical tensile test machinery, available in the market and a designed part. The test rig is composed by the machinery, which performs the principal functions of movement and force and two clamping devices for fixing the two work-pieces during the assembly. The clamping is designed to allow fixing different sizes and shapes of the work-piece as well as to let the clamp orientate the work-piece.

By gathering information through a market research and literature review, different design methodologies are applied in order to find the most suitable design. Thereafter, the final design is modelled and simulated in Pro/Engineer Wildfire 5.0 in order to analyse its most critical zones and to enhance the reliability of the design. It is concluded that the design fulfils the requirements established and contributes to the development of the novel assembly method. However, some parts may be refined, and as future work, the test rig could be prototyped and tested as well as implemented in the Company.

CERTIFICATE OF AUTHENTICITY

This thesis is submitted by Marina Muñoz García and Roberto Pérez Romero to the University of Skövde as a Bachelor Degree Project within Mechanical Engineering at the School of Technology and Society.

We hereby certified that all the material of this Bachelor Degree Project is our own work and the parts which are not, have been identified.

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LIST OF ABBREVIATIONS

❖ E collet Rego-fix	ER
❖ Female diamond knurl	F
❖ Friction coefficient	µ
❖ Left Hand knurl	LH
❖ Male diamond knurl	M
❖ Plus Minus Interesting	PMI
❖ Positive Negative Interesting	PNI
❖ Press Fitting method based on Knurling	PFK
❖ Right Hand knurl	RH
❖ Straight knurl	S
❖ Weighted Objectives Method	WM
❖ World Commission on Environment and Development	WCED

TABLE OF CONTENTS

ABSTRACT ..... *I*
CERTIFICATE OF AUTHENTICITY ..... *II*
ACKNOWLEDGEMENTS ..... *III*
LIST OF ABBREVIATIONS ..... *IV*
TABLE OF CONTENTS ..... *V*
LIST OF FIGURES AND TABLES ..... *VIII*
1. INTRODUCTION *1*
1.1. BACKGROUND *2*
1.1.1. Knurling process *3*
1.1.2. Press Fitting Method Based on Knurling (PKF) *4*
1.2. PROBLEM *5*
1.3. PURPOSE AND AIM *6*
1.4. GOALS FOR THE PROJECT *7*
1.5. LIMITATIONS *8*
1.6. METHOD *8*
2. LITERATURE REVIEW *11*
2.1. LATHING PROCESS *11*
2.2. OTHER ASSEMBLY PROCESSES *13*
2.2.1. Heat-cold method *13*
2.2.2. Laser welding method *13*
2.3. CREATIVE AND EVALUATING DESIGN METHODS *14*
2.3.1. Brainstorming *14*
2.3.2. Weighted Objectives Method *15*
2.3.3. Plus Minus Interesting method (PMI) *16*
3. CLARIFYING OBJECTIVES *17*
4. ESTABLISHING FUNCTIONS *20*
5. GENERAL STUDIES *23*
5.1. CREATING IDEAS *23*
5.2. DISPOSITION OF THE TEST RIG *25*
5.3. MARKET RESEARCH *27*
5.3.1. Test rig *28*

5.3.2. Shaft clamping tool 30
5.3.3. Ring clamping tool 33
6. CONCEPT GENERATION 35
6.1. CONCEPT ONE 35
6.2. CONCEPT TWO 36
7. EVALUATING CONCEPTS 38
7.1. EVALUATION OF THE TESTING MACHINE 38
7.2. EVALUATION OF SHAFT CLAMPING ALTERNATIVES 40
7.3. EVALUATION OF THE ALTERNATIVES FOR THE RING CLAMPING DEVICE 41
8. STRESS AND DISPLACEMENT ANALYSIS 46
8.1. CONSIDERATIONS 46
8.1.1. Selection of the critical zone 48
8.1.2. Symmetry 51
8.1.3. Boundary conditions and constraints 51
8.2. STRESSES ACCORDING TO VON MISES 52
8.3. DISPLACEMENT 53
8.4. ANALYTICAL SOLUTION 55
8.5. RESULTS 56
8.6. SIMULATION OF THE MOST CRITICAL SITUATION 57
8.7. DISCUSSION OF THE OTHER COMPONENTS 59
9. FINAL CONCEPT 62
9.1. ELECTRO-MECHANICAL TEST RIG 62
9.1.1. Dimensions 64
9.1.2. Specifications 65
9.2. SHAFT CLAMPING TOOL 65
9.3. RING CLAMPING TOOL 66
9.3.1. Materials and components 68
9.3.2. Attachment 70
9.4. FINAL 3D-MODEL 71
9.5. PRINCIPLE OF OPERATION 72
10. DISCUSSION 75
10.1. EVALUATION OF THE TEST RIG 75
10.2. SUSTAINABLE DEVELOPMENT 75

11. CONCLUSSIONS 78
12. FUTURE WORK 79
13. BIBLIOGRAPHY& REFERENCES 80
14. APPENDIXES 84
A. TIME PLANING AND WORK BREAKDOWN STRUCTURE 84
B. SIMPLE CHART OF EVALUATING CONCEPTS 86
C. SUMMARY OF THE PRINCIPAL CHARACTERISTICS 88
D. DRAWINGS 89
E. MATERIAL PROPERTIES 92
HARDENING STEEL AISI 8620 92
AISI-A2 TOOL STEEL 93
SOLID BRONZE 94
PTFE COMPOSITE 94
F. BUSHING CATALOG 96

LIST OF FIGURES AND TABLES

FIGURE 1: DIFFERENT KNURLING TOOLS (PENNTOOLCO 2012). 3
FIGURE 2: KNURLING PROCESS IN A LATHE. 4
FIGURE 3: DISPOSITION OF THE KNURLED REGION IN THE SHAFT AND IN THE RING. 5
FIGURE 4: RELATION BETWEEN A DESIGN PROBLEM AND ITS SOLUTION. 8
FIGURE 5: GENERAL STAGES IN THE DESIGN PROCESS. 9
FIGURE 6: STAGES IN THE DESIGN PROCESS FOR THE TEST RIG. 10
FIGURE 7: ANANTIQUE ARC LATHE (MUSEO DE LA MÁQUINA-HERRAMIENTA, 2013). 11
FIGURE 8: EXAMPLE OF A LATHE (ESCUELA POLITÉCNICA SUPERIOR, 2012) 12
FIGURE 9: STEPS FOR ACHIEVING THE WOM 15
FIGURE 10: OBJECTIVES TREE FOR AN ASSEMBLY TEST RIG 18
FIGURE 11: THE "BLACK BOX" SYSTEM MODEL FOR THE TEST RIG. 20
FIGURE 12: "TRANSPARENT BOX" SYSTEM MODEL 21
FIGURE 13: BRAINSTORMING PROCESS FOR A MACHINE WHICH HAS TO PERFORM THE NECESSARY MOVEMENT AND PRESSING FORCE TO ASSEMBLE THE WORK-PIECES. 23
FIGURE 14: BRAINSTORMING PROCESS FOR A CLAMPING DEVICE WHICH CAN FIX THE SHAFT AND THE RING. LEFT: MECHANISM TO FIX THE WORK-PIECES. RIGHT: DIFFERENT DESIGNS FOR FIXING AND ORIENTATING THE RING. 24
FIGURE 15: MORE EXAMPLES OF THE BRAINSTORMING PROCESS FOR A CLAMPING DEVICE WHICH CAN FIX AND ORIENTATE THE WORK-PIECES. LEFT: FIXING MECHANISM. RIGHT: AN IDEA TO ORIENTATE THE RING ON ITS CORRECT POSITION 24
FIGURE 16: VERTICAL TEST RIG: LEFT, SKETCH, RIGHT, FREE BODY DIAGRAM. 26
FIGURE 17: HORIZONTAL TEST RIG. LEF:SKETCH. RIGHT: FREE BODY DIAGRAM. 26
FIGURE 18: WORKSHOP PRESS MACHINE (SJMC MACHINE TOOLS, 2013). 29
FIGURE 19: EXAMPLE OF AN ELECTROMECHANICAL COMPRESSION-TRACTION TEST RIG (INSTRON, 2013). 29
FIGURE 20: ARBOUR MECHANISM (BAILEIGH INDUSTRIAL, 2013). 30
FIGURE 21: EXAMPLE OF A COLLET. (MACHINE TOOL ACCESSORIES & MACHINE WORK, 2008) LEFT: AN EXAMPLE OF A COLLET. RIGHT: AN EXAMPLE OF AN EXTERNAL COLLET WITH ITS CONICAL OUTER SURFACE AND INNER CYLINDRICAL SURFACE. 31
FIGURE 22: LEFT: THE INSTALLATION OF THE WORK-PIECE INTO THE CLAMPING DEVICE (WOODSON, 2012). RIGHT: EXAMPLE OF A JAW LATHE CHUCKS (MARIO PINTO, 2013). 32
FIGURE 23: EXAMPLE OF A GRIP FOR TENSILE TESTS (INSTRON, 2013) 33
FIGURE 24: SKETCH OF CONCEPT 1 36
FIGURE 25: SKETCH OF CONCEPT 2. 37

FIGURE 26: OBJECTIVES TREE OF CLAMPING RING DEVICE ... 43
FIGURE 27: PERSPECTIVE OF THE CLAMPING DEVICE FOR CLAMPING THE RING. ... 46
FIGURE 28: TENSION-DEFORMATION (ARCHIVO HISTÓRICO, 2002) ... 48
FIGURE 29:DISTRIBUTED LOAD APPLIED IN THE CLAMPING DEVICE ... 48
FIGURE 30: FORCES INVOLVED IN THE KNURLED REGION WHEN THE SHAFT IS IN CONTACT WITH THE RING. ... 49
FIGURE 31: TOP VIEW OF THE CLAMPING DEVICE WITH THE SHAFT. ... 50
FIGURE 32: EXPLODED VIEW OF THE COMPONENTS INVOLVED IN THE ANALYSIS. ... 50
FIGURE 33: BOUNDARY CONDITION OF THE MODEL ... 51
FIGURE 34:EXPLODED VIEW OF THE MODEL WITH THE STRESSES PRESENT ... 52
FIGURE 35: VIEW WITH THE MOST CRITICAL ZONES ... 53
FIGURE 36: DISPLACEMENT OF THE CLAMPING DEVICE. ... 54
FIGURE 37: EXPLODED VIEW OF THE STRESSES ACCORDING TO VON MISES FOR THE SECOND SIMULATION OF THE CLAMPING DEVICE ... 58
FIGURE 38: LOCATION OF THE HIGHEST STRESSES IN THE CLAMPING DEVICE ... 58
FIGURE 39: DISPLACEMENT OF THE CLAMPING DEVICE FOR THE SECOND SIMULATION ... 59
FIGURE 40: CONTACT ZONES AND MOMENTS PRODUCED IN THE JAWS OF THE CLAMPING DEVICE ... 60
FIGURE 41: CONTACT AREAS OF THE BRACES OF THE CLAMPING DEVICE. ... 61
FIGURE 42: FRONT AND REAR VIEW OF THE ELECTRO-MECHANICAL TEST RIG (INSTRON, 2013) ... 62
FIGURE 43: PRINCIPAL DIMENSIONS OF THE MODEL (INSTRON, 2013) ... 64
FIGURE 44: PNEUMATIC WEDGE ACTION GRIPS (INSTRON, 2013) ... 65
FIGURE 45: RING CLAMPING TOOL. ... 66
FIGURE 46: VIEW TO SEE HOW TO CONTROL OF THE ORIENTATION OF THE RING. ... 67
FIGURE 47: EXPLODED VIEW OF THE RING CLAMPING TOOL. ... 68
FIGURE 48: ATTACHMENT OF THE RING CLAMPING TOOL TO THE ELECTRO-MECHANICAL TEST-RIG. ... 70
FIGURE 49: WELDED PARTS ... 71
FIGURE 50: T-SLOT GUIDE RAILS OF THE CLAMPING TOOL FOR THE RING. ... 71
FIGURE 51: FINAL DESIGN FOR THE TEST RIG TO ASSEMBLE. LEFT WITH THE SHAFT, RIGHT WITHOUT THE SHAFT ... 72
FIGURE 52: OPERATION PART I ... 73
FIGURE 53: OPERATION PART II ... 73
FIGURE 54: OPERATION PART III ... 74
FIGURE 55: ASSEMBLED WORK-PIECE ... 74
FIGURE 56: WBS DIAGRAM ... 84
FIGURE 57: GANTT DIAGRAM ... 85
FIGURE 58: CROSS SECTION OF SKF PTFE COMPOSITE (SKF, 2013) ... 94

TABLE 1: SUMMARY OF THE MAIN IDEAS ACCOMPLISHED WITH THE BRAINSTORMING METHOD................ 25

TABLE 2: DIFFERENT POSSIBILITIES TO DESIGN THE TEST RIG FOR ASSEMBLING 25

TABLE 3: PMI CHART FOR PRESSING DEVICE ALTERNATIVES 39

TABLE 4: PMI CHART FOR CLAMPING SHAFT ALTERNATIVES 41

TABLE 5: EVALUATION OF EACH ALTERNATIVE FOR THE RING CLAMPING DEVICE 44

TABLE 6: MATERIAL INPUTS PROPERTIES: 47

TABLE 7: MAXIMUM DISPLACEMENTS OF THE CLAMPING DEVICE WHEN A COMPRESSIVE FORCE OF 50 KN IS APPLIED 54

TABLE 8: RESULTS OBTAINED IN THE ANALYSES PERFORMED IN THE CLAMPING DEVICE 57

TABLE 9: RESULTS FOR THE SECOND SIMULATION OF THE CLAMPING DEVICE 57

TABLE 10: TESTING SYSTEM COMPONENTS FOR 5960 DUAL COLUMN TABLE FRAME............................... 63

TABLE 11: CHARACTERISTICS OF THE MODEL 64

TABLE 12: OTHER SPECIFICATIONS FOR THE MODEL 5969 CHOSEN 65

TABLE 13: SPECIFICATIONS FOR PNEUMATIC WEDGE ACTION GRIP 66

TABLE 14: SPECIFICATIONS FOR THE CLAMPING DEVICE TO FIX A RING.. 67

TABLE 15: NUMERATION OF THE COMPONENTS OF THE RING CLAMPING TOOL....................................... 69

TABLE 16: SIMPLE CHART TO VALUE THE SUB-FUNCTIONS FROM LEVEL 1 OF THE CLAMPING DEVICE...... 86

TABLE 17: SUMMARY OF THE MAIN CHARACTERISTICS OF EACH PART FROM THE TEST RIG TO ASSEMBLE. 88

TABLE 18: MATERIAL PROPERTIES OF HARDENING STEEL AISI 8620 92

TABLE 19: MATERIAL PROPERTIES OF AISI-A2 93

TABLE 20: MATERIAL PROPERTIES OF SOLID BRONZE.. 94

TABLE 21: MATERIAL PROPERTIES OF PTFE COMPOSITE 95

1. INTRODUCTION

This thesis is part of a research project in collaboration with an external Company. It has a scientific-engineering character, and it is focused on the mechanical design and manufacturing area, where a test rig to assemble cylindrical elements based on knurling is under development. The assembled pieces are denoted work-pieces through this paper.

This diploma work project is performed for the entities which have an interest and a direct or indirect influence with the final results. These stakeholders are:

- The Company, specialists and other technicians.
- The University of Skövde.

The entities concerned will influence directly on how to perform the thesis. The results obtained must meet the requirements of the Company, save costs, and contribute to the development of the novel assembly method. For this, detailed drawings with their permitted tolerance for the elements designed, in addition to a descriptive catalogue with the machinery chosen, will be delivered to the Company.

This thesis is based in the need of developing a system to study the novel assembly process. The different steps to achieve it are exposed below.

An approach to different types of assembly processes is presented in chapter 2 in addition to an explanation referring to the lathing process. Furthermore, a definition about knurling process as well as how it is introduced in assembly processes is exposed in this chapter.

Later on this paper, brainstorming design technique is performed in order to generate preliminary ideas for the design. Subsequently, the ideas generated are applied in a market research so as to embrace the possibilities available in the market. It is concluded that the experimental setup has to be divided into three parts and therefore, three parallel studies are performed.

Thereafter, a design methodology denoted as *Rational Method* is applied according to Cross (2008). Firstly, the objectives to achieve by the test rig and its principal functions are defined. With this, as well as the results achieved in the market research, it is possible to select and evaluate the different alternatives for the design. It is has to take into consideration the division made of the test rig in order to be able to choose the most suitable solution. It is concluded that some parts can be chosen from industrial catalogues, but there is an important part which has to be design due to the fact that there is not a current system which fulfils all the necessary aims established previously. Then, a 3D model as well as drawings with the design of the device is carried out, taking into account the specifications of the Company in addition to the aims established along this paper.

Afterwards, a stress and displacement analysis of the solution reached for the designed part is accomplished in order to know in depth the reliability of the solution. This process is achieved analytically with determinate simplifications and the assistance of *Pro-Engineer Wildfire 5.0* software.

Finally, when all the parts of the test rig are defined, designed and analysed, discussion, conclusions and a collection of possible further work are presented.

1.1. BACKGROUND

For a long time, manufacturing has been considered as an essential part of the society, but compared to other forms of business; it can be contemplate as a fairly new technology. Manufacturing process involves all the methods used to create work-pieces. The selection among different manufacturing methods depends on the design characteristics and materials of the work-piece as well as the economics resources. Even, the same piece can be manufactured by different methods obtaining the same mechanical results.

The test rig designed in this paper is responsible of manufacturing a work-piece in accordance with an assembly method in which knurling takes part. This method is classified as a joining method, specifically denoted as pressing fit method. Normally, pressing fit joining processes are developed by thermal expansion or by applying a pressing force (Bralla, 1999). In this case, the piece is manufactured by pressing force.

Usually, this joining process is achieved due to the friction originated between the entire contacting zones of the components involved, as interference fit between them. In this case, as an innovation of this method, the contact surfaces are partly knurled before the assembly process takes place. Thus, the manufacturing process selected to work with through this thesis is denoted as Press Fitting method based on Knurling process (PFK).

1.1.1. Knurling process

Knurling is a cold forming manufacturing process which is performed by knurls that are pressed against a rotating cylindrical work-piece. Knurls are rollers made of high-hardened tempered steel with shaped stretch marks on their outer surface. These engrave, with a considerable pressure, the area to be treated. Knurls are usually disposed in a holder which is attached to the tool-holder of the lathe.

This process generates a corrugated surface on the work-piece. Its grooves can be performed in different directions depending on the type of the tool chosen, as shows figure 1.

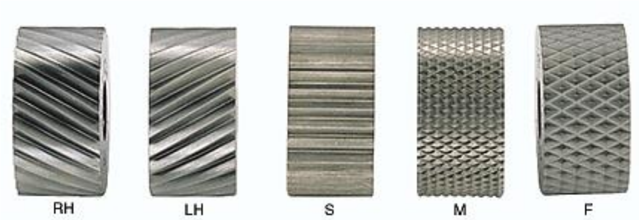


Figure 1: Different knurling tools (Penntoolco2012).

In the figure, five different knurled regions are exposed. In the centre, there is a Straight knurl (S). Leftwards, there are two diagonal knurls; and a Right and a Left Hand (RH and LH) respectively. Rightwards, Male diamond knurl (M) with raised pyramids and Female diamond knurl with depressed pyramids are shown (Feng, 2004).

Straight knurling is divided into two types, depending on the direction chosen:

- Radial knurls are used when the knurled longitude in the piece is coincident with the width of the knurl used.
- Longitudinal knurling occurs when the knurled longitude exceeds the width of the knurl. In this case, the knurl must be bevelled at its ends.

This process is widely used in industry for many applications. Some of these include repairing of undersized and oversized shafts, in addition to driving serrations and splines. Knurling is also used in pieces involved in manual works to diminish the possible slippage produced between the operator and the work-piece. Another extended purpose involves manufacturing and assembling processes.

Figure 2: Knurling process in a lathe.

This cold forming manufacturing process is carried out in lathes with knurls of different sizes and drawings that cut and wrap around the cylindrical metallic work-piece. As it is shown in the figure exposed above, the process starts by clamping the work-piece to a lathe. Furthermore, the device responsible of fixing it has to rotate in order to achieve the process. In the figure, a LH knurl installed in the tool-holder of the lathe is engraving the work-piece. To accomplish a proper performance, the work-piece has to be lubricated during the process as shows figure 2. Therefore, an important aspect to take into consideration in any knurling application is the set-up (Feng, 2004). In order to perform this, it is necessary to:

- Use an appropriate quantity of lubricant. Knurling generates some extreme pressures with an improperly lubrication (Formroll, 2003).
- Use rigid knurls and holder, in order to be rigid enough to withstand the rolling forces applied.
- Form a deeper and wider impression on the first revolution is the key to achieve a correct knurling operation. The proper execution of the groove in the knurled region is usually established after just one complete revolution of the cylindrical work-piece.
- Control the rotation speed during the knurling process in order to assure a proper execution of the process.

1.1.2. Press Fitting Method Based on Knurling (PKF)

The processing technology denoted as Press Fitting method based on Knurling (PFK), is used for assembling cylindrical work-pieces. It is an advanced and novel joining technique which is being implemented increasingly. In order to study this technique, a test rig to assemble is being developed. It is specific equipment developed on the basis of knurling joining technology. In this present case, it is focused in the joining area between a shaft and several rings.

This new method is based on joining different parts: one hollow shaft and a determined number of rings. These latter are shaped and hardened to their final size. Then, the inner surface of the ring and the outer surface of the shaft are knurled with perpendicular straight knurling. The disposition of the knurled region of both work-pieces is exposed in figure 3.

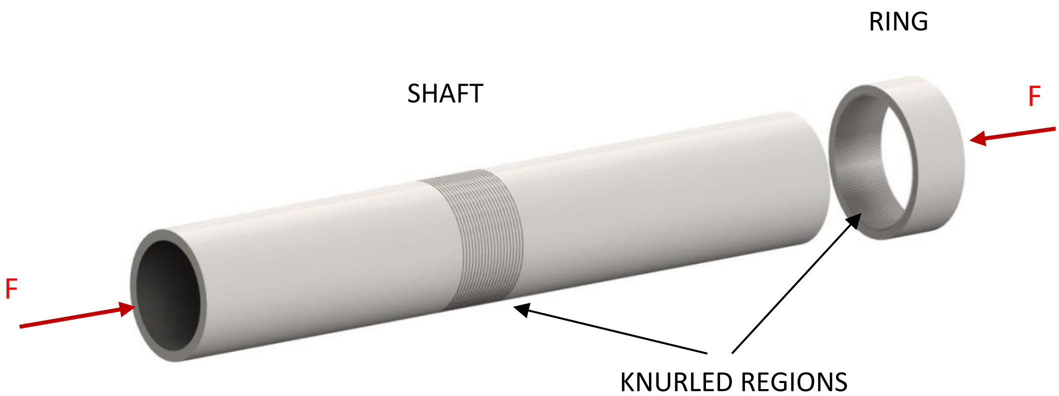


Figure 3: Disposition of the knurled region in the shaft and in the ring.

Once both work-pieces are knurled, they are clamped into the test rig. Thereafter, an axial pressing force is exerted between the work-pieces so as to achieve the joint, which is formed by the deformation produced in the knurled region. It is considered that the hardness of the rings has to be higher than the shaft, therefore, to accomplish the joint; the teeth of the knurled area in the shaft are deformed and broken. Furthermore, it is necessary to take into consideration the compressive force used, which depends on the dimension of the teeth and the width of the knurled region (Jian, 2008). Therefore, an optimal fit between both parts is required in order to guarantee the correct future performance of the work-piece.

1.2. PROBLEM

Nowadays, a great quantity of engineering enterprises performs activities of transformation which manufactures work-pieces and machinery. They are responsible of receiving raw materials and, with a series of processes, bring an added-value to the final product.

Traditionally, similar pieces as the work-piece involved on this paper, are manufactured from one solid metal piece, through a process of cutting, milling, and hardening. Since this method produces numerous turnings in addition to not to have the possibility of decreasing the weight of the work-piece, a new method based on knurling is under developed to optimize the use of the material, and consequently, save costs. This mounting method offers a wide range of significant benefits with respect to other techniques which will be described later on this paper. The principal advantages are: a reduction in processing costs, a remarkable weight lightening, high in production efficiency, an optimal combination of the materials as well as design and manufacture flexibility.

1.3. PURPOSE AND AIM

The principal goal of this thesis consists of designing a test rig to assemble cylindrical work-pieces in order to investigate the joining process by means of knurling so as to implement the novel method instead of manufacturing work-pieces with the traditional lathing method exposed in the previous section.

Regarding to the economical aspect, the objective is to reduce the cost of the product as well as minimize the cost involved with the assembly line. *"Manufacturing costs is a key determinant of the economic success of a product"* (Ulrich, etal. 2000). In the engineering field, specifically in the design, assembly and manufacturing area, economic success depends on the margin earned between the cost of making the product and the final cost of itself. Basically, the increase of benefits is due to these two factors:

- Significant reduction of the weight of the work-piece.
- Save of material during the manufacturing process, due to lack of turnings generated.
- Increase of production in the assembly line. More work-pieces are produced per unit of time with the novel joining method.

The final weight of the work-piece is also an important aspect to take into consideration, not only due to the economical aspect, also by the fact of the importance of the future functionality of the machinery where the work-piece is installed in addition of its benefits associated (Van den Brink, et al., 2001). Some of the industrial sectors involved with the manufacture of this type of work-piece are the automotive, naval and aerial sector. According to Tolouei (2009), the final mass of a vehicle is an essential aspect to determine the fuel consumption as well as its relationship with the environmental aspect. DeCicco (1996) estimated a reduction in the fuel consumption of 6% by decreasing a 10% in the weight of a 1300 kg passenger car. Other secondary factors in which the weight of the work-piece, and consequently of the machinery, takes part involves security factors and efficiency in the performance of the machinery.

1.4. GOALS FOR THE PROJECT

This thesis within mechanical engineering aims at designing an experimental setup to study the joining process of PFK. The design includes the choice of an already existing test rig with a redesigned part. The requirements for an optimal machine design are to:

- Maintain the surfaces between the shaft and the rings parallel during the assembly process.
- Insert the rings with a correct phase angle taking into consideration a permitted tolerance of one degree.
- Insert the rings in the correct sequence and axial position taking into consideration a permitted tolerance.
- Have the capacity of assembling different sizes of rings taking into consideration that the dimensions in the shaft are invariable.
- Apply the appropriate force to achieve the joint. As different sizes of rings are assembled, it is demanded a pressing force between a minimum of 16 kN and a maximum of 50 kN.
- The pressing force has to be measurable with a maximum error of 10 N.
- The displacement of the shaft through the rings has to be controllable in order find the correct position of the assembly in the knurled region. The minimum value measurable is 1 mm.

The joint should also be able to perform its load transmitting function during its specified life.

1.5. LIMITATIONS

This thesis comprises the aims established in the previous section; however, due to the limitation in time and the nature of the project, some limitations are required. These are:

- Design the mechanical fundament of an experimental test table for assembling cylindrical pieces.
- Secondary elements such as fasteners and other elements that are not included in the assembly process are excluded in the design.
- The connection of electronic elements and electric facilities are not included in this paper.
- The limits in the application of the assembly force will be also established to assure a correct joint during the process and a proper performance of the final piece in the future.

These limitations will influence in the way of designing the product.

1.6. METHOD

In this section, determinate engineering design methodologies called *Rational Methods* (Cross, 2008) are exposed. In order to do this, it is presented engineering design methodologies called *Rational Methods* (Cross, 2008) in order to generate and evaluate a design solution for a test rig responsible for assembly cylindrical bodies by means of knurling. The methods consist in analysing the problem and divide it into sub-problems which generate sub-solutions so as to achieve the overall solution. Figure 4 shows the relation problem-solution established.

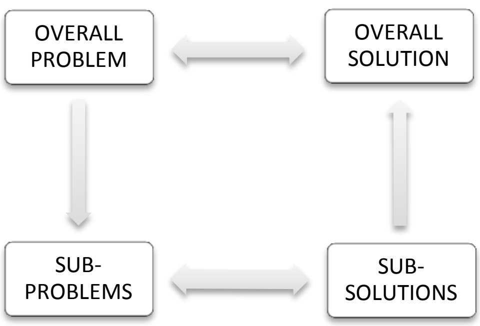


Figure 4: Relation between a design problem and its solution

There is a wide range of rational methods in order to fulfil all the aspects concerning the design process. In this paper, a series of stages are performed in order to accomplish the best design solution. According to Cross (2008), a procedure composed by seven logical stages with their respective methodology should be performed so as to cover the whole design process. Figure 5 shows the entire procedure performed.

Thus, the first step in the process consists of determining objectives with the method denoted as *Objectives Tree.* The reason for which this process is required is due to the necessity of clarifying the objectives of the product, the sub-objectives and the relationship between them. The second step consists in establishing the functions of the test rig. In order to perform this, a method called *Function Analysis* is used. Then, it is necessary to establish precise requirements for the product and determinate its principal engineering characteristics in accordance with the company requirements. Thereafter, it is started the generating and evaluating alternatives process in which *Chart Weighted Objectives (WOM*) and *Plus Minus Interesting (PMI)* methods are used. Finally, in order to increase the final value of the product, reducing costs and/or improving secondary characteristics, a last step to improve details is performed with the help of the *Value Engineering* method.

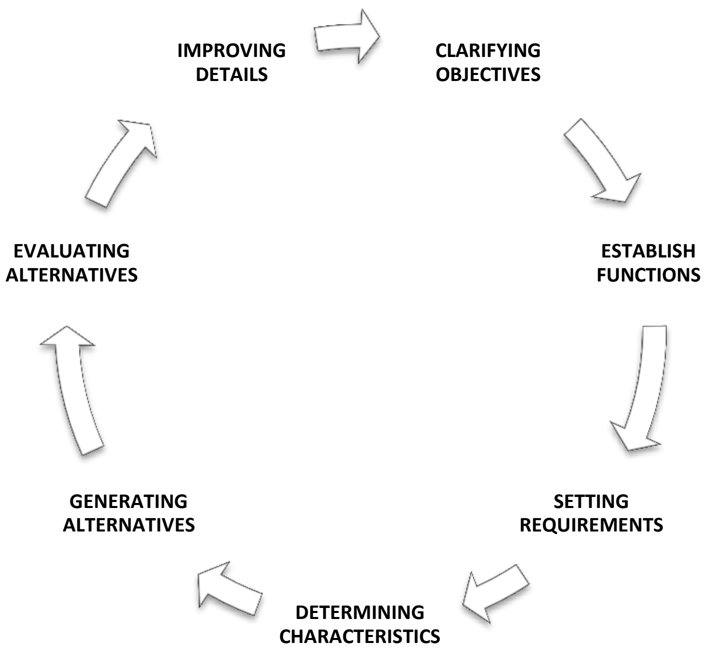


Figure 5: General stages in the design process

Therefore, there are seven rational steps to accomplish the design of a product. Cross also states that this method is not invariable. Depending on the type of product in addition to the specifications of the user, the steps presented in figure 5 can be reduced or expanded. However, all the steps chosen and achieved have to be demonstrated logically. In figure 6, it is shown the procedure chosen to accomplish the design of the test rig, purpose of this paper.

In the application of the *Rational Method*, it is also possible to include creative methods in order to complement the design process of the product. Methods such as *Brainstorming* (Osborn, 1979) in addition to a market research are also included in the stages to achieve.

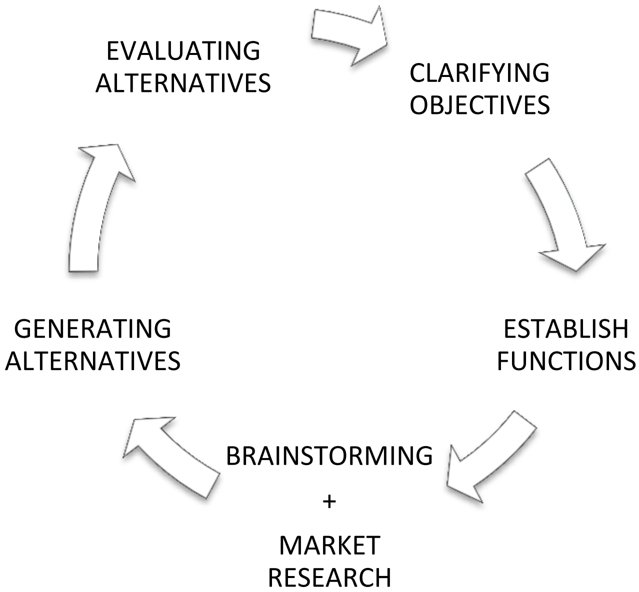


Figure 6: Stages in the design process for the test rig.

Therefore, the process of designing a test rig to assemble starts by clarifying objectives as well as establishing the principal functions of the machinery. Then, the process of generating ideas begins with the *Brainstorming* method, and thereafter, with a market research. In this step, the test rig will be divided into three different parts, and three parallel researches will be performed so as to find the most suitable solution for the design problem. Every part performs different indispensable functions and can be designed separately, but taking into consideration that all together forms a unity. Consequently, it was conclude that it is possible to use some catalogue parts available in the market, but other part will have to be designed completely. Thus, when the generation of ideas is done and different alternatives are generated, they are evaluated to conclude with the best design. This evaluation is also performed by separating the three main parts of the test rig.

2. LITERATURE REVIEW

In this chapter it is exposed several studies which are the base to understand determinate aspects of this project. Firstly, different manufacturing processes are presented. Lathing process is explained for being the traditional method used nowadays to manufacture the work-piece of this study. Other alternatives methods are also defined. Furthermore, some design methods are presented and used for creating and evaluating the design developed.

2.1. LATHING PROCESS

Nowadays, factories manufacture steel work-pieces by means of lathing automatically a solid work-piece until its final shape. Even the Company manufactures the work-piece of this study with this method. The machine-tool in which lathing processes take place is the lathe. It is characterized by the rotation of the tool-holder in addition to the different movements performed during the execution of the turning process.

Its origin lies in the primitive pottery wheel, and possibly, its specific first configuration for manufacturing pieces by removing material, is close to the figure exposed below. The machinery shown was not a machine-tool in the modern sense of the term, since it does not have any structural unity and all the elements are operated manually. Additionally, this arc lathe presents a considerable disadvantage with respect to the turning blade: the alternation of the direction of rotation (Escuela Politécnica Superior, 2012). Thus, this machinery was used to work with abrasive tool, being therefore, more a grinder or a buffing than a lathe.

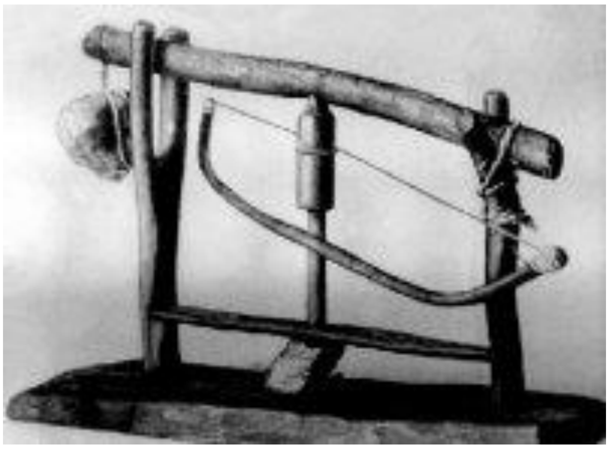


Figure 7: An antique arc lathe (Museo de la Máquina-Herramienta, 2013).

Subsequently, manual operated lathe is arisen. Its movement is transmitted with a handle and determinate pulleys in order to reach the tool-holder, fixed to the machine. The tool is supported directly by a second operator, by using as support and guidance of the movement a ruler which is firmly attached to the frame of the lathe.

The current configuration of the horizontal or parallel lathe was achieved in the first half of the nineteenth century through the British Haudslay and Roberts. Its performance is achieved by pulleys from the shaft of a steam engine and it is characterized by its automatics feeds and the capacity of screwing with the blade. Nowadays, lathes consist of the following elements (Escuela Politécnica Superior, 2012):

- Bench or rack: It is the body of the lathe. It is characterised by its resistance as well as supporting the elements of the machine. It is usually attached to the ground of the workshop. In figure 8.

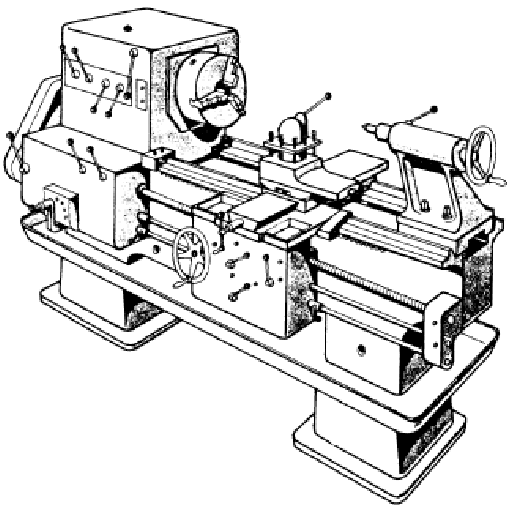


Figure 8: Example of a lathe (Escuela Politécnica Superior, 2012)

- Headstock and tailstock: They are typically denoted as fixed and mobile headstock, respectively. Its principal function consists on clamping and positioning the work-piece as well as performs the rotatory movement.
- Motor and transmission: They are the elements which control the selection of the velocity.

The operations conducted fundamentally in lathes are turning, boring, threading, grooving, parting, facing, drilling, knurling and taper turning.

The principal advantage offered by manufacturing a work-piece with this method is stiffness provided to the final piece. Nevertheless, this process generates an important quantity of turnings which is an evidence of the waste of material produced.

2.2. OTHER ASSEMBLY PROCESSES

In this chapter, different assembly and manufacturing technologies such as heat-cold and laser welding method are exposed. The selection of these manufacturing methods was realised taking into consideration the similarities in shape and function with the final work-piece of this study. In both cases, rings and shafts are assembled, the difference remains in the type of assembly process used.

2.2.1. Heat-cold method

In heat-cold assembly method, the rings are disposed with its inner diameter under-sized, as well as being provided with serrations. Firstly, the process starts by locating the rings on a shaped dummy shaft. Then, according to Anderson, et al. (2002), the rings are clamped and the dummy shaft is removed. Thereafter, the rings are heated and their serrated inner diameters start to being shaped to their final size and concentricity. Finally, a shaft, at ambient temperature, is introduced through the holes of the rings, and subsequently the rings are cooled so that they are shrunk and fitted onto the shaft.

2.2.2. Laser welding method

In laser welding assembly method, the process starts by manufacturing the rings and the shaft separately through a process of cutting and milling. Then, the assembly process takes place. The procedure includes a gas metal arc welding torch as well as a laser arc welding laser head. Both elements are placed close to the work-pieces (Devers, et al. 2012). The work-pieces are spaced rather close so that the melted material produced by the torch overlaps with the melted material emerged from the laser head. Both melted material emerged combine in order to create a hybrid laser arc weld which is the responsible of the assembly of the work-pieces.

Although laser welding has certain advantages in the assembly process such as a reduction in size and weight of the piece, there are also some disadvantages associated with laser welding in assembly processes. According to Daub (2000), this technology has high investment cost in addition to heat distortion effects that must be taken into consideration. There are also many other critical factors that must be tightly controlled in order to ensure that the correct weld seam is performed. These factors include quality of the material, geometrical accuracy, material cleanliness, alignment and pre-assembly of the components. For this, alternative assembly methods such as knurling are being developed (Coban, et al. 2009).

2.3. CREATIVE AND EVALUATING DESIGN METHODS

2.3.1. Brainstorming

Brainstorming is probably the oldest and most well-known designing technique. It was created by Alex F. Osborn and introduced in his book *Applied Imagination* published in 1953. Osborn tries to discard the habitual ideas of the mind of the designer to produce a series of fresh ideas in order to be able to choose the most suitable. This well-known technique is used to treat specific problems by creating preliminary concept ideas of the product as well as stimulating the designers to produce varied ideas in a short time.

Even though Osborn stipulates that this method should be applied with a designing group composed of twelve members, it has been shown that the ideal number of members oscillates between four and seven people, being also practical groups between two to ten members as well as individual. In this case, the brainstorming was performed by two people (Osborn, 1953).

Hence, the steps to achieve the process are composed of four basic rules which are defined as follows (Técnicas de creatividad, 2003):

I. **Suspending judgment and remove any criticism.** When an innovative idea has been suggested, it is not permitted any critical comment. Every idea has to be noted, and it will not be evaluated until later. It is almost innate being instantly analytic, pragmatic and convergent with the own thoughts and ideas; so in some cases, this rule presents difficulties to be achieved.

II. **Thinking freely.** It is essential to provide freedom of expression in order to add different points of view for the new design of the product. It is a good point take into consideration wild and impossible ideas. Actually, the most practical ideas usually emerge from ludicrous thoughts due to the fact that the mind is out of the habitual limits and it lets improve and create other solutions.

III. **The quantity is important.** There are two reasons why it is necessary to generate a large number of ideas. Firstly, it is common that the initial ideas are not very innovative. They are often unimaginative and unviable. Hence, it is necessary to create more creative ideas in order to find the best solution to the designing problem. Secondly, the more ideas, the easier it is to choose the best one.

IV. **The multiplier effect**. In some cases, taking the idea of your partner and improving can be a stimulus in order to find the final concept. Thus, it essential to combine and conceive improvements.

2.3.2. Weighted Objectives Method

Weighted Objectives Method (WOM) is a design methodology which is divided in determinate steps, according to Cross (2008). Figure 9 presents these steps achieved.

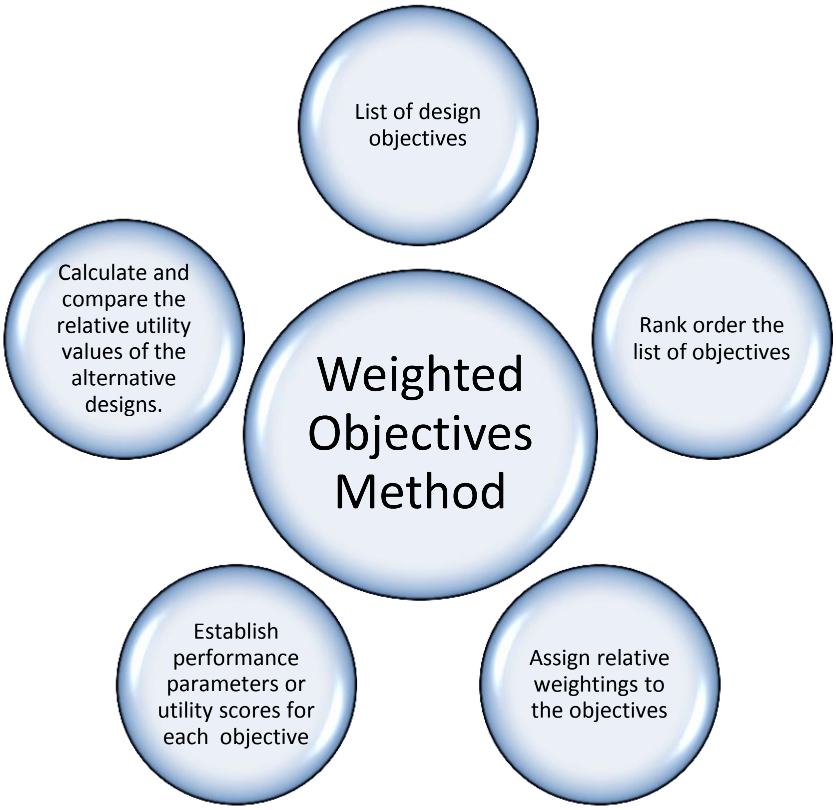


Figure 9: Steps for achieving the WOM

In order to develop the WOM, the first step consists of listing the objectives which are required for the design. Secondly, the sub-objectives of each level, *Rank order the list of objectives,* are listed. Then, every member from the same level is assessed and compared. Sometimes, when the members are only two, the comparison can be done with an estimated method. Whether the members of one group are more than two, the assessment is performed with a simple chart (Appendix B).

Thirdly, a numerical value to each sub-objective is assigned in the step denoted as *Assign relative weightings to the objectives.* In order to developed it, it is used a 0-1 scale, where the sub-objectives are placed. Then, each sub-function has to be measurable or estimated in order to realize the evaluation of the qualities of each characteristic of the design alternatives (*Establish performance parameters or utility scores for each of the objectives).* It is used a 1-4 scale to establish the range of possibilities, where 1 is the minimum value and 4 the maximum value of each sub-function.

Finally, the alternatives are valuated and compared so as to find the most scored one (*Calculate and compare the relative utility values of the alternative designs).*

2.3.3. Plus Minus Interesting method (PMI)

According to Bono (1982) and Hildebolt (2009), sometimes it is hard to evaluate the principal features of a design when different alternatives are generated. The idea which the author bases his studies consists of dividing the features of each alternative into positives, negatives or interesting qualities and consequently valuate them. In order to denote the classification performed, it is used *Plus (P)*, for the positive characteristics, *Minus (M),* for the negative ones, and *Interesting (I)* for the additional positive ones.

In order to develop this analysis of characteristics, a table is done with the alternatives in the first row and the valuation positive, negative and interesting in the first column. This table is denoted as PMI chart and can be found in section 7.

3. CLARIFYING OBJECTIVES

When it is necessary to design an engineering product for a company, it is essential to establish some aims to perform the design successfully. Sometimes, the company manager only knows which type of product is required in addition to a lightly idea of some details. Other times, the company lets a wide range of open possibilities to analyse them and conclude which is the best solution for the problem. In those cases, the starting point in the design is a non-defined problem with some vague known requirements.

Therefore, the first step will be clarifying the design objectives of the product. A rational design method called *The Objectives Tree* (Cross, 2008) is applied for this, in order to provide a clear and useful statement of the aims. The procedure starts by preparing a list of design objectives. Then, the list has to be ordered into sets of higher-level and lower-level objectives. Finally, the relationships between the aims are defined and a diagrammatic tree of objectives is made.

Following this procedure, the objectives tree has been generated taking into account the already-known design specifications from section 1. Now, it should be possible to divide every objective into sub-objectives. The hierarchical relationship and connections are shown in the tree of objectives exposed in figure 10.

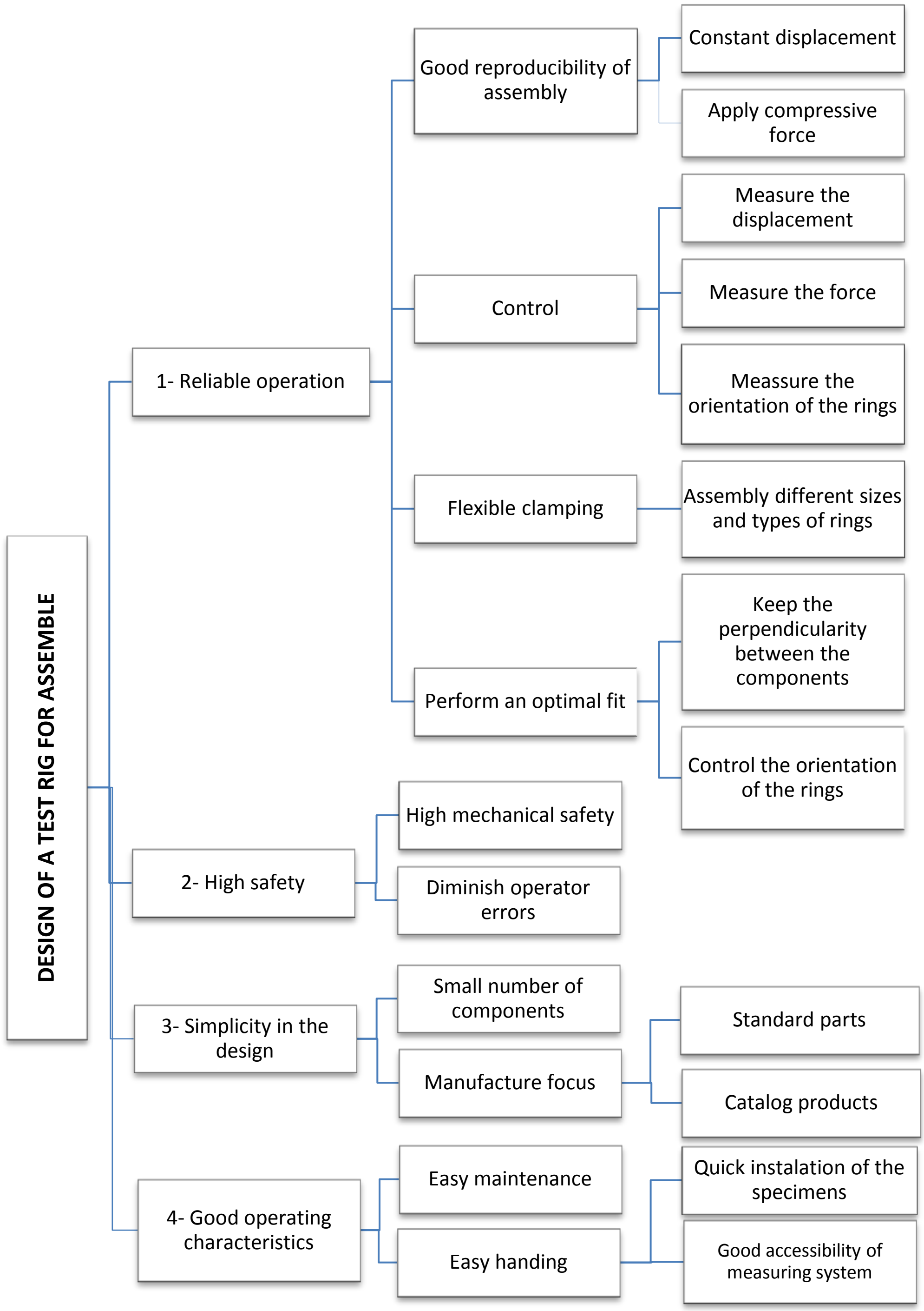


Figure 10: Objectives tree for an assembly test rig

Each connection link drawn in the figure represents that a lower-level objective has to be fulfilled in order to achieve a linked higher-level objective. Therefore, if the diagram is read from the left to the right, it expresses how an objective can be achieved. Conversely, if the tree is read from the right to the left, it represents why a sub-objective is required.

The objectives tree decided for the test rig to assemble, as shows the figure exposed above, is composed by four main requirements located in the first level: it has to perform a reliable operation; it has to be characterized by its high safety and good operating properties as well as simplify the components designed. Every requirement is composed by the objectives and sub-objectives established previously. The second level in the tree represents the principal aims in order to design the product. The following branches in the tree indicate the sub-objectives necessary to fulfil every objective.

Obtain a reliable operation is the first requirement to fulfil. It is considered as the main purpose to perform the design of the test rig. As the diagram is read from left to right, the objectives connected to this aim express how it should be achieved. Therefore, to perform a good reproducibility of the assembly, it is necessary to apply a compressive force in addition to produce a constant displacement. By the same procedure, the rest of the objectives are represented. The second objective consists of designing a controllable test rig. The pressing force, the stroke of the shaft in addition to the orientation of the rings has to be measurable. The next principal aim expresses that different sizes and types of rings has to be clamped. Thereupon, flexibility in clamping is required. As last objective to achieve the first requirement, it is necessary to perform an optimal fit for the elements to be clamped. In order to do this, it is required to keep the perpendicularity between the components as well as control the orientation of the rings.

High safety is assumed as a second requirement of the test rig. The importance of this one is due to the fact that the test rig is designed with the purpose of making tests, and an operator has to interact with the machinery. The breakdown of these objectives is to achieve high mechanical safety in the components and diminish the operator errors.

The third requirement has as aim to simplify the designed product. In order to achieve that, some sub-objectives are established such as using small number of components in addition to use standard parts and catalogue products.

As final requisite, good operating characteristics in the test rig for assembling are necessary. This is accomplished by having an easy maintenance and handling of the machinery. This one is realized with a quick installation of the work-piece to assemble and a good accessibility of the measuring system.

4. ESTABLISHING FUNCTIONS

In the previous section, it was stated certain objectives to perform the design. As it is seen from the *Objectives Tree* in figure 10, engineering design problems usually can be considered in different levels to satisfy all the requirements of the product. Sometimes, it is also very useful consider the essential functions that the design is required to satisfy in order to provide certain freedom to the designer and perform different alternative solution proposals which fulfil the functional requirements.

In the present section, it is exposed an engineering design method called *The Function Analysis Method* (Cross, 2008) in order to determine the essential functions of the test rig to assemble. The essential functions are those that the test rig has to satisfy without taking into account the physical components used. Thus, the starting point for this method consists of focusing in what has to be accomplished instead of how has to be done. For this, a black box with inputs and outputs data it is represented in the figure 11in order to help to establish the necessary functions.

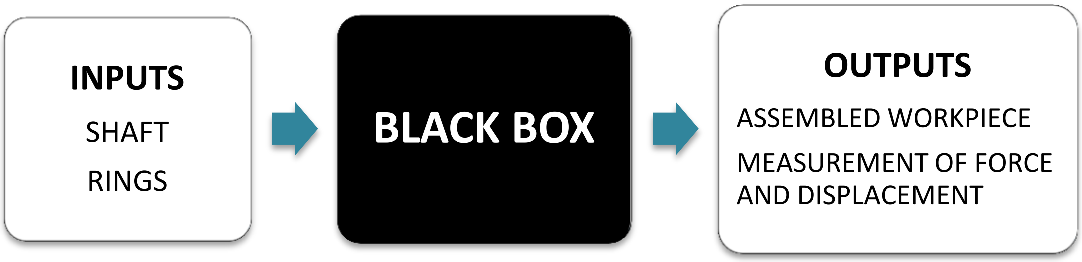


Figure 11: The "black box" system model for the test rig.

In the figure, the "black box" comprises the overall functions in order to converting the inputs into outputs (Cross, 2008). In this case, the inputs are the cylindrical parts to be assembled, which are the shaft and the rings. After a determinate process, the output is the final assembled work-piece as well as the measurement of the necessary parameter such as the pressing force.

Then, it is time to divide the functions enclosed in the "black box" into sub-functions and establish the connection between them. It is only necessary to include the relevant functions. Secondary tasks have been omitted to not to deviate from the output. In figure 12, the elements contained in the "black box" are represented.

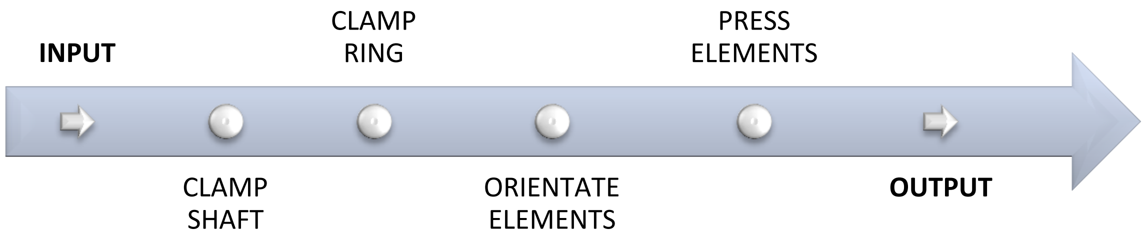


Figure 12: "Transparent box" system model

As it can be observed from the figure exposed above, it is presented the process of assembling, its principal functions and the interaction between them. With this, it can be described in a simplify way the assembly process. It starts by fixing the knurled shaft into the test rig. Later, one of the knurled rings is also clamped, and thereafter, is orientated on its correct position. Once all the elements are fixed, the assembly process is initiated. The shaft, which its external knurled diameter is concentric with the inner knurled diameter of the ring, performs an axial displacement to achieve the joint of both work-pieces. The joint is done by the deformation produced in the knurled area. The knurling process is executed previously; therefore, it is not included in the procedure. Finally, the parameters involved in the process such as the pressure required to accomplish the joint and the displacement of the shaft are measured and checked.

From now, the designing objectives with their respective level of importance in addition to the essential function and sub-functions of the test rig for assembly have been defined. Thus, the next step consists of identifying a suitable component for each function described before which satisfies the objectives described in the previous section.

The orientation of the elements is an operation that can be located in either clamping device. There are three possibilities, done by the shaft, the rings or both. Done by both is a refusing option because it would include many components, so it does not fulfil the simply design requirement, and it would perform a complex usefulness in order to control them. The rings are easier to orientate due to the irregularity on its outer shape, in addition, its size and weight are smaller and lighter respectively than the shaft; therefore can be easier to handle. Thereby, the clamping tool for the rings is also selected to perform the orientating function.

So henceforth, the design it will be divided into three different parts in order to search the appropriate component to perform the functions and objectives established successfully. These parts are:

- A clamping element responsible for fixing one knurled ring in addition to orientate it in the correct position.
- A clamping component which fixes the shaft in addition to maintain the perpendicularity with the other elements.
- A machine which performs the necessary movement and pressing force to assemble the work-pieces.

In order to do this, a market research as well as a brainstorming process is initiated. This study is achieved taking into consideration the established division in three different parts of the test rig to assemble.

5. GENERAL STUDIES

General studies are performed before developing any design of the test rig. They are needed in order to focus the design with initial ideas and configuration of the setup machinery as well as a market research of each component.

5.1. CREATING IDEAS

By applying these steps for the test rig to assemble, the brainstorming method to generate ideas is performed. From chapter 4, the test rig is divided into three principal parts in order to achieve the best designing solution. Thus, brainstorming was developed separately in order to simplify the process of selection of the design and find the most adequate solution for each function of the machine. Figures 13, 14 and 15 expose some sketches from the brainstorming process for every part of the test rig.

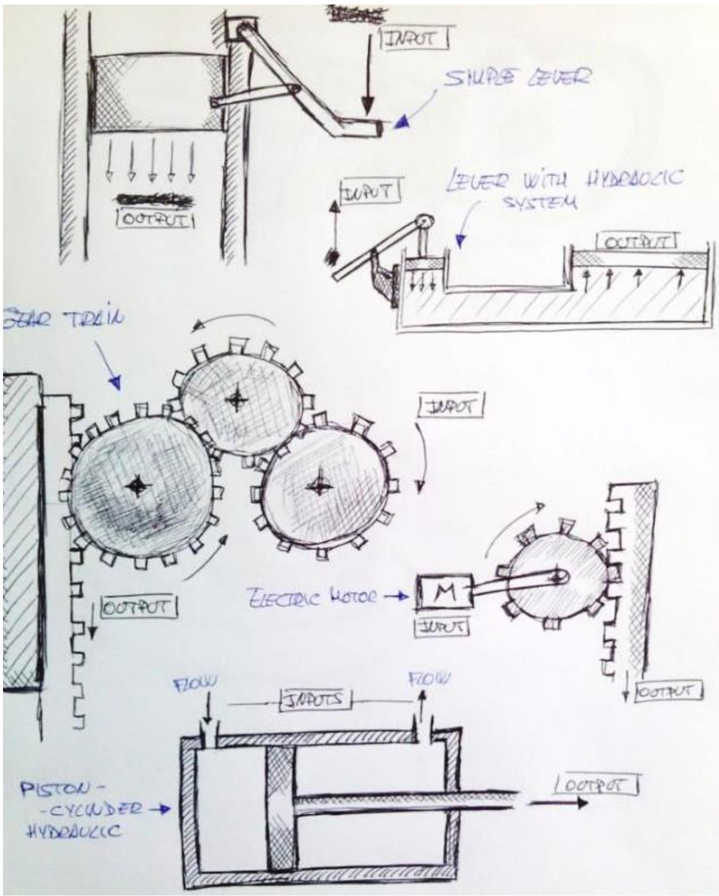


Figure 13: Brainstorming process for a machine which has to perform the necessary movement and pressing force to assemble the work-pieces.

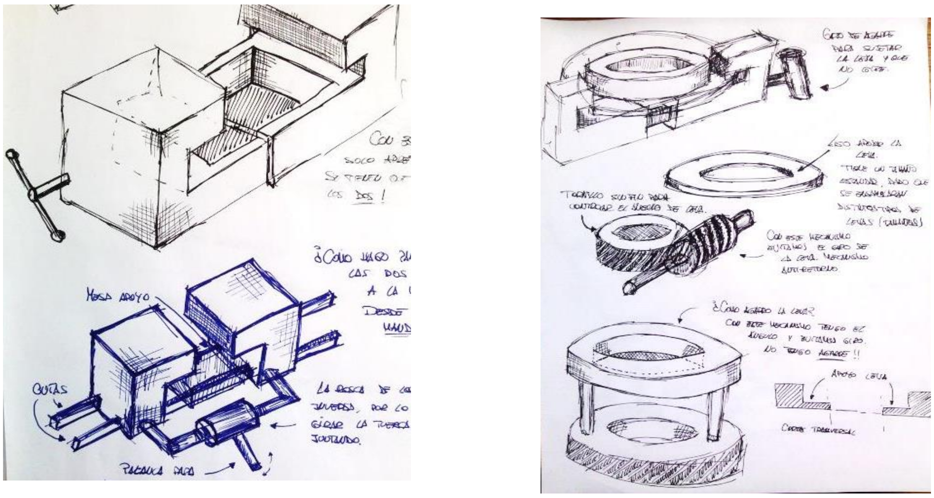


Figure 14: Brainstorming process for a clamping device which can fix the shaft and the ring. Left: Mechanism to fix the work-pieces. Right: Different designs for fixing and orientating the ring.

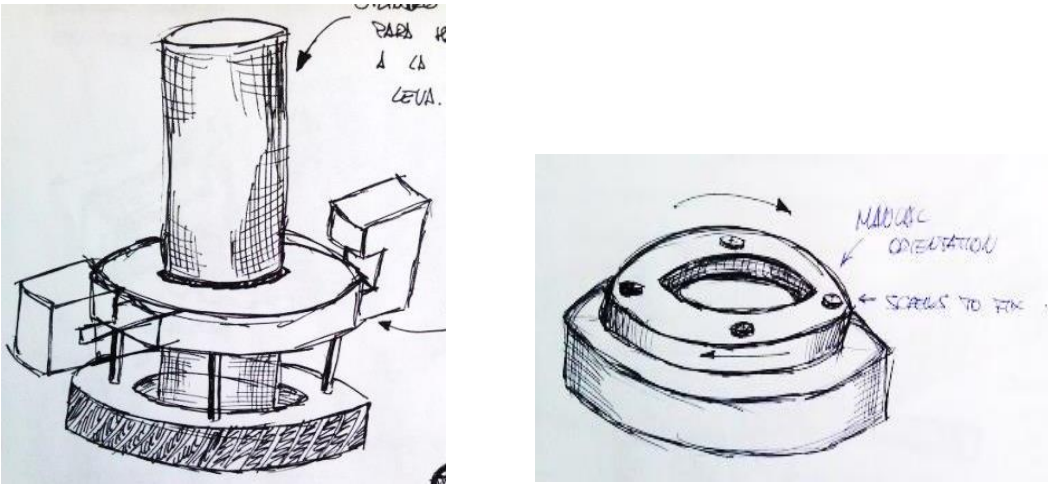


Figure 15: More examples of the brainstorming process for a clamping device which can fix and orientate the work-pieces. Left: Fixing mechanism. Right: An idea to orientate the ring on its correct position

The brainstorming process was developed in different temporized sessions both in a group as well as individually. According to the most of the designers (Cross, 2008), the best manner to transmit ideas is by using visual information, such as drawings or sketches. Hence, by observing the figures exposed above, it can conclude that the pressing force can be executed with an electric or manual input. Other distribution could be mechanical or with hydraulic facilities. Furthermore, it can be observed in the sketches the mechanical idea of clamping and orientating the work-pieces manually. With these alternatives kept in mind, it can be possible to develop the test rig to assemble in many different ways. In table 1, it is exposed the main conclusions achieved by means of using the brainstorming method to generate ideas.

Table 1: Summary of the main ideas accomplished with the brainstorming method.

Power input for the test rig	Characteristics for the clamping
Manually	Manual handing of the component
Electrically	Mechanical fundament in the design
Hydraulically	Simplicity
	Resistant materials
	Easy handling

5.2. DISPOSITION OF THE TEST RIG

There is a wide range of open possibilities to design the machinery of this study since the Company does not restrict any design aspects. Certain specifications have been provided, but different solutions can be performed in order to achieve the final design. Table 2, establishes a first classification of the different dispositions of the machinery as well as the direction of its principal movement.

Table 2: Different possibilities to design the test rig for assembling

Principal movement	Disposition of the machinery
Performed by the shaft	Horizontal
Performed by the ring	Vertical
Performed by both work-pieces	Inclined

It is selected the shaft to perform the principal movement due to the fact that there are more difficulties by doing it with the ring. As it is known, the ring can present irregularities on its shape in addition to have to be placed in a specific orientation. If the ring would perform the movement to achieve the joint, it would have to do many functions and the probability of making an inappropriate assembly would increase. If the ring rotates to orientate itself, it is more complicated to make the assembly movement too. Hence, it is selected the shaft to perform the movement in order to accomplish the joint by introducing it through the ring.

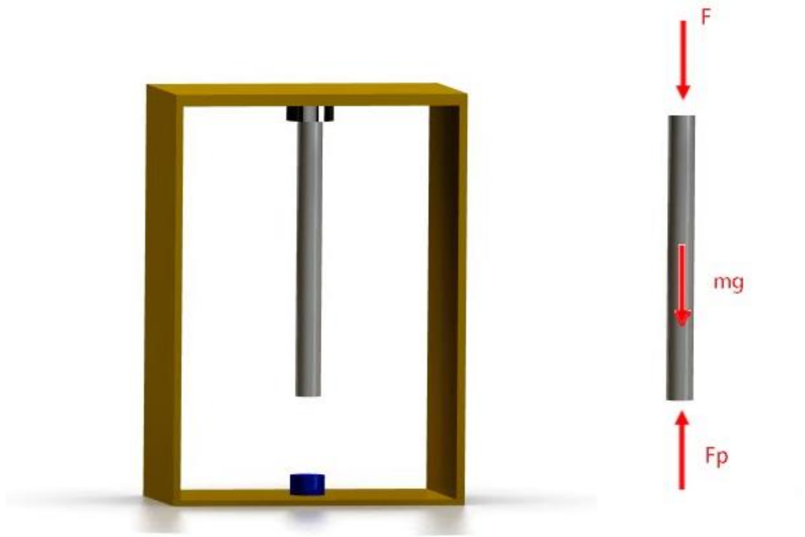


Figure 16: Vertical test rig: Left, sketch, Right, free body diagram.

The disposition of the components involved in the assembly process is also an important task to solve. Diverse arrangements are possible: vertical, horizontal, inclined or upside down. The elements involved are the knurled shaft and ring. Thereby, if it is chosen the vertical distribution, both work-pieces are placed vertically and the weight would help to achieve the assembly process in addition to keeping the perpendicular disposition between the pieces as shown in figure 16.

On the other hand, if the work-pieces are placed horizontally, the weight does not contribute to the assembly process neither to keep the elements perpendicular. Moreover, a bending moment is it created in the clamping area of the shaft. Figure 17 displays the forces and moments involved for a horizontal test rig.

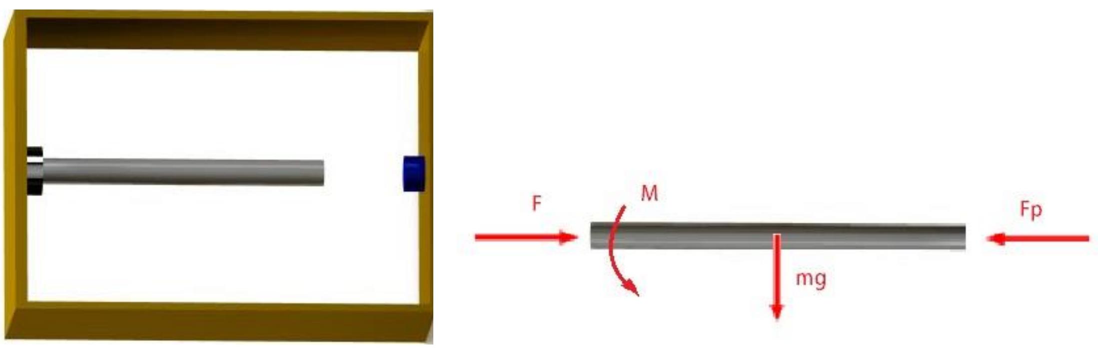


Figure 17: Horizontal test rig. Left: sketch. Right: Free body diagram.

The inclined position of the test rig is refused due to the difficulty which may present for clamping the element and keep the components perpendicular.

In all cases, it has to comply with the principle of static equilibrium and Newton's first law (Beer, 2006) which states that the net force and net torque in the system is zero. Therefore, the *first condition of equilibrium* [1] as well as the *second condition of equilibrium* [2] is equal to zero.

$$\sum \vec{F} = 0 \qquad [1]$$

F is the vector summation of forces acting on the body and it can be translated to:

$$\sum \vec{V} = 0 \qquad [1.1]$$

$$\sum \vec{H} = 0 \qquad [1.2]$$

Equation [1.1] expresses that the sum of the vertical components of the forces has to be equal to zero. Simultaneously, equation [1.2] estates that the sum of the horizontal components of the force has to equals zero.

$$\sum \vec{M} = 0 \qquad [2]$$

In this case, equation [2] represents the sum of the moments present in the system has to be zero.

5.3. MARKET RESEARCH

When the project was initiated, the knowledge about the engineering field to address was not enough. For this reason, it was necessary to make a research about knurling, knurling in assembly processes and a comparison with other assembly methods. Now, with all this new information, the clarification of the objectives and functions, it is necessary to perform a market research in quest of stimuli, analogies in the market (Ulrich, et al. 2000) as well as evaluate the available options in the industry.

The process starts by separating the three main parts of the test rig (Section 4). Hence, it is performed a principal research about industrial machinery, in order to find a test rig, in addition to the clamping components. Other secondary elements which have been helpful to provide new designing ideas are not included.

5.3.1. Test rig

Firstly, it is started an investigation about industrial machinery which can perform the necessary functions to accomplish the assembly of the work-pieces. In order to do this, it is required to take into account the objectives established (Section 3) and the specifications of the Company (Section 1.4). Furthermore, it is considered the vertical disposition of the test rig according to chapter before. Thus, three possible alternatives are selected in order to evaluate them and conclude with the best designing solution. These are:

- Hydraulic workshop press
- Electromechanical tension-compression testing rig.
- Arbour press

I. Workshop press

A workshop press is a machine-tool with a hydraulic performance (Figure 18). It can be controlled automatically or manually. Its principal function consists of pressing elements. It is composed by a cylinder with a piston inside which is responsible of compressing the work-piece against a work-table. This process is possible thanks to hydraulic oil installed which is activated with a manual hydraulic pump (Vargas, 2011). The metallic structure of the machine is composed by two lateral columns placed on a firm base which supports and balances the pressing device. This machinery is commonly used in automobile applications, especially for maintenance and repair.

Figure 18: Workshop press machine (SJMC Machine Tools, 2013).

This machine is characterized by its hydraulic performance with the capacity of applying controllable pressures from 5 kN up to 1000 kN depending on the model chosen Moreover, it has a flexible work-table to place and fix the element to work with.

II. Electromechanical compression-traction test rig

A tensile-compressive test rig is machinery used for testing specimens. It can perform a multitude of tests for various materials, industries and components according to internationals standards, such as ASTM, ISO or EN (Instron, 2013) depending of the specifications of the Company. It is mainly used to evaluate the mechanical properties in materials and components by using compression, tension, fatigue, torsion, impact, hardness and flexure tests. Figure 19 shows an example of this machinery chosen from the company Instron.

Figure 19: Example of an electromechanical compression-traction test rig (Instron, 2013).

The machinery is characterized by its broad range of functions and possibilities as well as its variety of models and sizes. It can be installed different accessories such as work-tables, clamping devices and load cells in accordance with the requirements of the user. Hence, it is possible to test different sizes, heights and materials of work-pieces and specimens, fix them efficiently as well as apply a range of forces between 0.5 N up to 600 kN. It is also possible to control and measure accurately the force, the velocity applied and the vertical displacement performed in the testing process.

III. Arbour pressing mechanism

A simple mechanism composed by racks and pinions is presented. The model performs the principal vertical movement of the test rig. It consists on a gear which rotates thanks to an axel connected to an electrical motor. The racks installed control the vertical movement. Figure 20 shows a photo of the fundament of this mechanism.

Figure 20: Arbour mechanism (Baileigh Industrial, 2013).

The arbour press presented in the figure above can apply a force of 55 kN. In this case, it would be possible to control the speed in addition to the displacement achieved in the process. Conversely, it would not be possible to control the pressing force applied. The mechanism is used in the fabrication of different work-pieces and components such as bushings, bearings.

5.3.2. Shaft clamping tool

The second step to achieve a competent engineering design consists of deciding which type of clamping tool is necessary to fix the shaft. In order to do this, it is performed a second market research which gives rise to new ideas as well as standardize and commercial tools to fulfil the requirements of simplicity, accuracy, security and efficiency.

Firstly, some preliminary conditions has to be stipulated taking into consideration the prerequisites of the company (section 1.4), the tree of objectives from section 3 and the main functions which has to be achieved in the test rig defined in section 4. Thereby, the principal properties, specifications and reasoning for the design of the clamping element are gathered along this paper and used in the research.

Then, the research was accomplished and it was concluded with these three possible designing alternatives for fixing the shaft:

- Collet
- Jaw lathe chuck
- Grips for tensile tests

I. Collet

A collet is a holding device with a collar shape which is placed around a cylindrical piece. To achieve the fixing, it is exerted a considerable clamping force on the piece with the help of an external collar with a conical outer surface and cylindrical inner surface as shows figure 21.

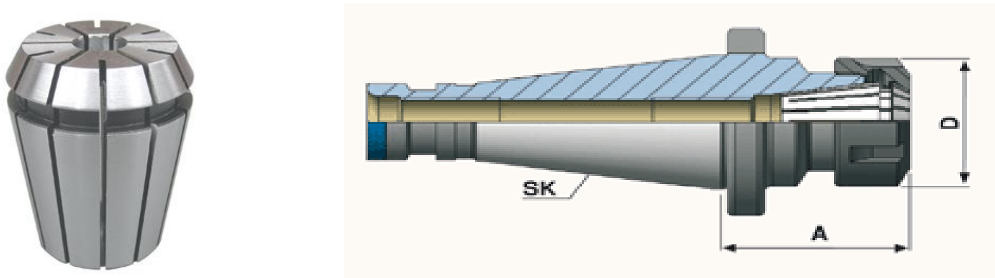


Figure 21: Example of a collet. (Machine Tool Accessories & Machine Work, 2008) Left: an example of a collet. Right: An example of an external collet with its conical outer surface and inner cylindrical surface.

The procedure starts by squeezing a work-piece with the inner surface of the collet which is contracted to a slightly smaller diameter. In the figure, it is shown a collet made of spring steel with a determinate number of cuts along its length to allow it to expand and contract. This device is commonly used to hold tool or work-pieces for many applications in various types of industries, such as woodworks, metallic working, ER collets, craft hobbies artists, semiconductor works and it can be also found in internal combustions engines.

The principal characteristics of using this clamping device are that it offers a strong clamping force as well as presenting resistance against being detached when it is tightened. Furthermore, the work-piece can be clamped quickly in addition to be self-centred. On the other hand, a collet presents a narrow clamping range; consequently, a large number of different types of collets are required in order to hold different diameters of work-pieces.

II. Jaw lathe chuck

A jaw lathe chuck is an accessory of a lathe responsible of clamping a work-piece (Figure 22). It is composed by three jaws situated in the chuck body. They are opened and closed at the same time maintaining their radial position to adjust the piece to be clamped. To centre the piece, it is necessary to open the jaws with the help of a pinion driven by an adjustment screw. To control the centring, it is used a dial gauge installed.

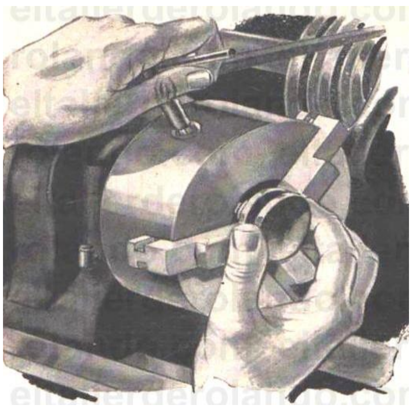


Figure 22: Left: The installation of the work-piece into the clamping device (Woodson, 2012). Right: Example of a jaw lathe chucks (Mario Pinto, 2013).

The device is characterized by a simple and fast adjustment. At the same time, it is effective, presents a flexible clamping in addition to have an easy performance.

III. Grips for fatigue and tensile tests

Mechanical wedge action grips are used for material testing applications. It is used both flat and round work-pieces. Its design is characterized by having the capacity of gripping the work-piece without transmitting axial pre-loading (Instron, 2013). This is accomplished by moving the faces of the jaws just in the horizontal direction. Each grip is mechanically operated. Its pressing force is applied taking into consideration the direction of the jaw faces. The movement performed to clamp the work-piece is achieved by four socket cap screws placed inside of the grip head.

As it can be observed in figure 23, there are two jaws responsible of performing the movement and grip the work-piece.

Figure 23: Example of a grip for tensile tests (Instron, 2013)

This device is characterized by providing a plurality of materials to be clamped, such as metals, plastics and composites as well as performing an accurate and perpendicular attachment. Furthermore, it is possible to clamp round or flat pieces of different sizes. A load cell can be also placed in the device to control the force applied.

5.3.3. Ring clamping tool

As a last stage to achieve in this section of market research, a quest to find a mechanism which performs the functions assigned to clamp and orientate the ring is started. In order to do this, main functions and specifications for this part of the test rig are stipulated by performing the same procedure as in the previous elements. Hence, the principal characteristics to fulfil are to:

- Select a clamping tool which enables the attachment of a ring with its inner diameter of 60 mm and a possible irregular outer surface.
- Consider the possibility of fixing different sizes and shapes of rings.
- Select the orientation of the ring.
- Have an easy and manual operation.

In this case, after the market research it was concluded that there are not any product available in the market which fulfils as this requirements. Therefore, a clamping device to fix the ring is developed in order to accomplish all the specifications of the Company. In the following sections, it will be described the design process for this clamping device as well as its design evaluation.

6. CONCEPT GENERATION

The process of generating ideas is one of the most tedious tasks when a product is required to be developed. Theoretically, this consists of creating novel products or machines; but in practice, sometimes, is enough by modifying an existing product according to requirements. According to the test rig, the generating idea is developed with the assistance of the brainstorming, which is done in section 5.1. In this section, the design is focused on the clamping device for the ring, motivated by the results of the market research, from section 5.3.

After the ideas obtained from the brainstorming method, two concepts are developed for clamping the ring into the test rig. For a future evaluation, the concepts are presented by showing a division of its parts, these are:

- A rotatory part: In both concepts, the structure is composed by three principal elements; an inner fixed cylinder element, a rotatory cylinder and an element capable of avoid the friction between them.
- A part for clamping: The idea is to create a simple, flexible and manual fixation of the ring.

6.1. CONCEPT ONE

The first concept was generated by the composition of standard pieces as well as unique elements completely designed.

Firstly, the rotatory part is composed by a table with two T-slot guide rails in which two jaws are disposed, see figure 24. The jaws are the elements responsible of clamping the ring. These are controlled by a double threaded screw which works thank to the manual performance of an operator. To achieve the fixation, one hand it is only necessary.

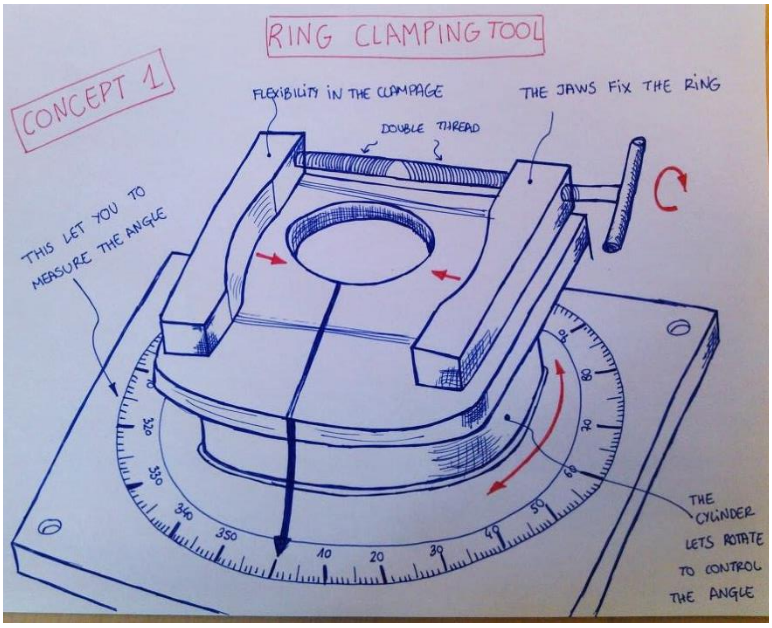


Figure 24: Sketch of Concept 1

In order to control the concentricity of the inner diameter of the ring and the inner diameter of the clamping device, the shaft involved in the assembly process is used. Thereafter, the orientation of the ring is required. Thus, a rotatory element is designed in order to perform the movement. It is composed by five main elements; an inner fixed cylinder responsible of attaching the device onto its base, an external rotatory cylinder which performs the movement in addition to a planar bearing denoted as bush which is inserted in between in order to provide a bearing surface for the rotatory application. There are also two braces around the cylinders which control the rotatory movement. The opening and closing of the clamps is performed manually with the help of a screw. As the last component, there is a table with an angle wheel drawn on its surface to be able to measure the orientation. This latter is also the element which supports the other ones as well as fixes the device into the test rig.

6.2. CONCEPT TWO

The second concept is not significantly different from concept one. Its main difference lies in the clamping part. Instead of having a single double threaded screw which controls both clamps, there are two screws to work with. Hence, the operator requires two hands to fix the ring. Figure 25 exposes the design of concept two.

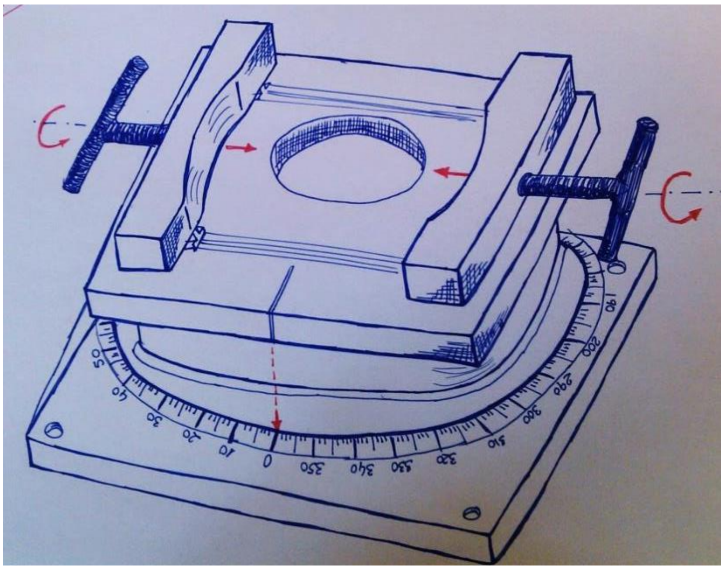


Figure 25: Sketch of Concept 2.

In this case, the rotatory part is the same as in concept one.

7. EVALUATING CONCEPTS

A designer must be capable of developing solutions to a determinate design problem; nevertheless, creating ideas is not enough to present a final product. The designer has to be able to choose the best design alternative, among all of them. Thereby, the designer should possess a good criterion in order to select the best solution. Thus, the question is: *what is the best solution according to*? In order to decide which one is the most suitable, the *Weighted Objectives Method (WOM)* and *Plus Minus Interesting (PMI)* method are used.

7.1. EVALUATION OF THE TESTING MACHINE

After presenting all the alternatives to develop the test rig, it is required to select the best concept. PMI method is used to find the best solution. In order to do this, a ranking list with the requirements needed is developed, according to an order of priority. Therefore, the first ones are considered essential and the last ones secondary.

Once done the ranking of requirements in addition to the PMI chart, the alternative which has more requirements in the positive (Plus) column as well as less in the negative (Minus) one will be the final solution.

The goals which have to be fulfilled by the test rig are exposed in the following ranking. Thus, the requirements are to:

- Dimension of the machine in order to permit operates with the work-pieces, in addition to install a work-table located 1 m above the ground.
- Keep perpendicular the shaft and the rings during the assembly process.
- Control the compressive load.
- Control the displacement.
- Develop an easy handle.
- Have low cost.
- Develop a mechanical operation.

Once the requirements are established, the advantages and disadvantages of each machine are evaluated in the following table:

Table 3: PMI chart for pressing device alternatives

	Plus	Minus	Interesting
Arbour Press	• Easy handle • Mechanical tool • Low cost	• Problems to fix the work-piece. It is necessary a minimum stroke of 1 m. • Non-controllable stroke. • The pressing load is not controllable.	• Manual operation
Workshop press	• Controllable load • Hydraulic pressure • Constant displacement	• Problems of dimensions • Non-controllable stroke • Non-mechanical	• Used in workshops.
Electro-mechanical test rig	• Accuracy guaranteed in the process of testing • Include measure and control of load and stroke • Possibility of attaching round and flat work-pieces • Flexibility in the accessories installed.	• High cost • Non- mechanical	• Used in essays of traction and compression

The first model evaluated is the arbour press. It is characterized by its mechanical design, with a simple manual handle, in addition to its low cost. The perpendicular displacement is realized by its internal rack-pinion mechanism (Section 5.3.1). Nevertheless, its main disadvantage, after doing the market research, is that it is not found any standard arbour press with the dimensions needed to operate with the work-pieces. Thus, it should be necessary to develop a customizable arbour press. In addition, due to its mechanical disposition, the machinery would perform an inaccurate control in the pressing load and the stroke of the shaft.

The second model is the work-shop press. This type of machine has a widely used in workshops, keeping perpendicular the movement of the work-piece along the stroke. The pressing force of this machine is developed with hydraulic facility, which performs a pressure which is controlled by a gauge. The workshop press does not have the required dimensions standardized, so, although the work-table is movable, the machine has not the space needed to perform the assembly process. In addition, this type of machine does not include any dispositive to control the displacement of the shaft.

In order to solve the disadvantages of each model mentioned, the solution would be to develop customize machinery, attaching external accessories to supply their deficiencies. For this reason, both models are refused.

Electro-mechanical compression-traction test rig gathers all the requirements exposed previously. The dimensions of the machine are enough to assembly the work-pieces, with a movable work-table which can be located one meter above the floor. In addition, this type of machine, are used to perform traction and compressive tests, so the supplier assures the accuracy of the perpendicular movement, guarantees the minimum force necessary as well as a constant displacement. The load is controlled by a load cell attached in the upper part of the machine. The two last requirements of the ranking list are not fulfilled, which are to have low cost and possess a mechanical design; however, these ones are not essential goals.

Thus, the machinery chosen in order to develop the principal functions of the test rig of this study is the Electro-mechanical test rig, supplied by Instron.

7.2. EVALUATION OF SHAFT CLAMPING ALTERNATIVES

Once it is done the market research of this part of the test rig, an evaluation based on the PMI method is executed. The first task consists of identifying the requirements of the shaft clamping device, which are listed below. Then, the PMI chart is presented in table 4.

- Support the weight of the shaft
- Keep perpendicular the shaft with respect to the hole of the ring.
- Have the possibility of clamping a work-piece of 60 mm diameter
- Fix the shaft with the necessary force and not create clearances
- Use a standard product
- Replace the work-pieces quickly
- Possess a mechanic fundament

Table 4: PMI Chart for clamping shaft alternatives

	Plus	**Minus**	**Interesting**
Collet	• Mechanic • Strong clamping • Offer detached when it is not tightened • Quick replacement of the specimens • Many standard sizes	• Does not fulfil dimensional requirement • Non clamping flexibility	• Standard uses
Jaw lathe chuck	• Mechanic • Strong clamping • Quick replacement of the specimens	• Use secondary tools	
Grips for fatigue and tensile tests	• High precision • Strong clamping • Standard accessories from Instron	• Expensive • Non-simple control	

After doing the PMI chart, the 3 alternatives fulfil the requirements presented above. Thus, the selection of the most suitable is performed by the comfort of attaching the clamping device into the electro-mechanical test rig chosen. In this case, the grips for fatigue and tensile tests are manufactured by the same supplier as the test rig, so it is easier to choose elements from the same machinery to connect the parts. Thus, the device responsible to the clamping part of the shaft is the grips for fatigue and tensile tests.

7.3. EVALUATION OF THE ALTERNATIVES FOR THE RING CLAMPING DEVICE

After doing a brainstorming, a market research and a concept generation, two final alternatives of the clamping tool are evaluated according to WOM. By considering the *Objectives Tree* from chapter 3, a new list of design objectives, specifically for the clamping alternative devices, is developed. Once the method is finished, the alternatives with the highest punctuation are chosen as the final solution.

Taking into consideration the main objectives exposed in figure 26, the most important one is to perform a *Reliable operation* due to it involves the essential characteristics to design the clamping tool of the ring. These ones are to: keep perpendicular direction, control the orientation, and dispose flexibility in the clamping part in order to assemble different sizes and types of rings. Thus, in order to develop a reliable operation, generation of ideas was taken into account, even before, in brainstorming and market research.

On the other hand, the remaining principal objectives from the same level are considered at the same grade of importance. High safety includes mechanical safety and diminishing of operator mistakes. As the clamping is meanly mechanic, this one is considered with a high score. Another objective to achieve is to perform a simple design in order to manufacture it easily. It is accomplished with small number of components and standard parts. To conclude, good operating characteristics such as easy handing and maintenance are required. Furthermore, easy handing is realized with a quick installation of the work-pieces in addition to have good accessibility of measuring system

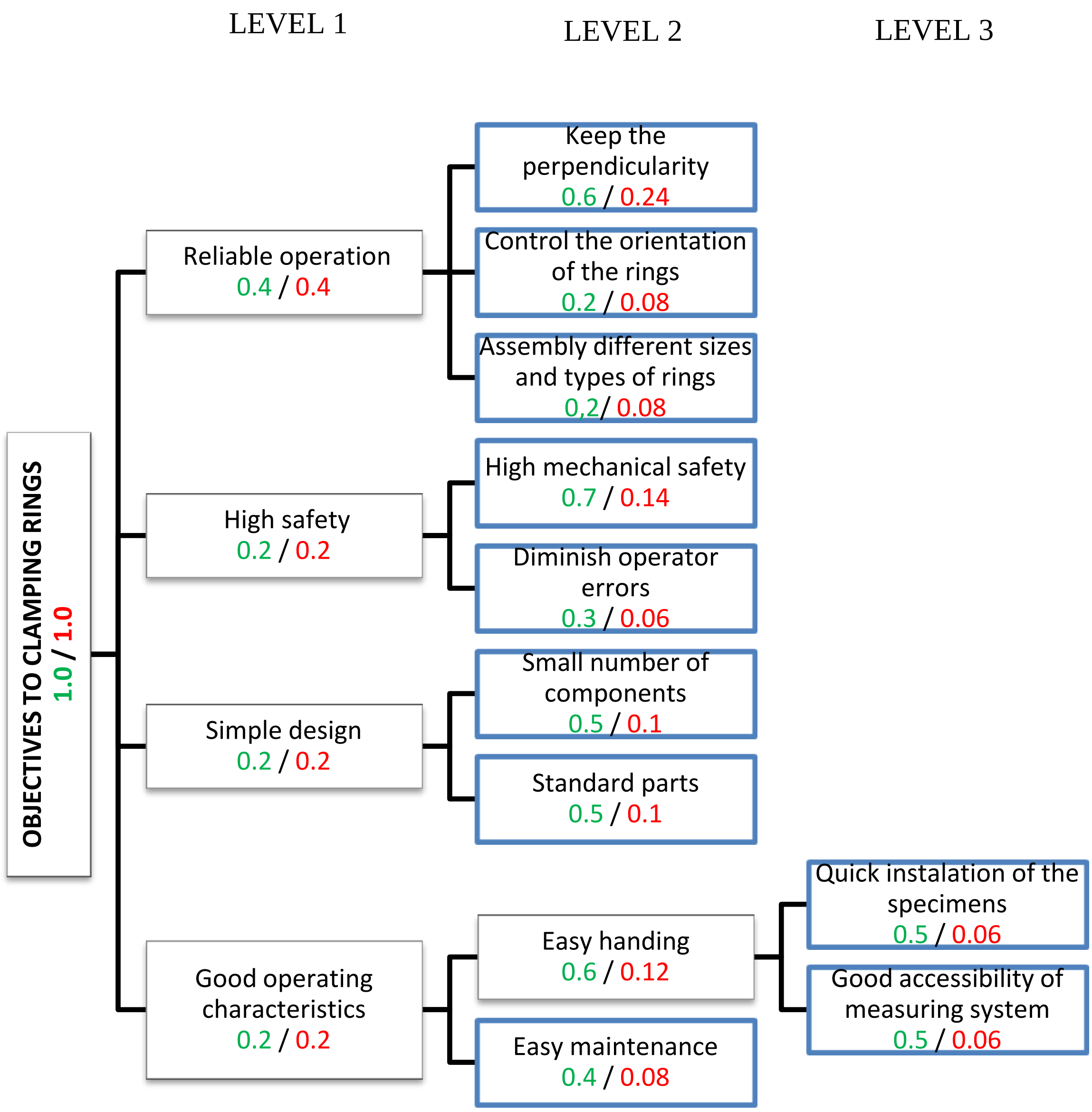


Figure 26: Objectives Tree of clamping ring device

Figure 26 shows the list of sub-functions, in a ranking position with the weights established. The ranking position is descendent, so the most important sub-objectives are in the upper position. The weighed scores are located underneath each sub-function. The first number, coloured in green, represents the fraction in relation with the level, and the reddish shows the fraction of the entire classification. The score to each sub-function is developed with a simple chart in appendix B.

Once the score of each sub-function is made, it is proceeded with the own evaluation of each alternative, as it is exposed in table 5. In the first column of the table, the sub-functions, which are framed in a blue box in figure 26, are presented. The second and third columns display the evaluation of each sub-objective with a score between 1 and 4, for the two proposed concept designs, A and B. In the two last columns, the result of multiplying the scores by the weighted sub-functions, are exposed. The total score of each evaluation are exposed in the last row.

Table 5: Evaluation of each alternative for the ring clamping device

SUB-OBJECTIVES	OPTION A [1,4]	OPTION B [1,4]	Evaluation A	Evaluation B
Keep perpendicularity	4	4	0.96	0.96
Control the ring orientation	4	4	0.32	0.32
Assembly different sizes and types of rings	4	4	0.32	0.32
High mechanical safety	4	3	0.56	0.42
Diminish operator errors	4	2	0.24	0.12
Small number of components	4	3	0.4	0.3
Standard parts	3	4	0.3	0.4
Quick installation of the work-piece	4	3	0.24	0.18
Good accessibility of measuring system	4	4	0.24	0.24
Easy maintenance	4	4	0.32	0.32
TOTAL SCORE			**3.9**	**3.58**

Both alternatives fulfil the first main objective: *Reliable operation*. This requirement it was taken in account in the brainstorming and market research, in order to create ideas. Thus, either alternative has the maximum score in this first objective.

The difference between options is focused the clamping zone for the rings. Option A operates with a double thread worm, which moves two jaws at the same time, while option B achieve the clamping with two thread worms one per jaw. This difference procures distinct scores in safety, design and characteristics of the model.

High mechanical safety is considered higher in A than in B, because the last one needs more operations due to the two thread worms. At the same time, this one produces more operator errors. Using small number of components is achieved in option A, but option B is considered to use more standard parts.

In the test rig it is necessary to replace the work-pieces at every assembly process, so quick installation is required. Furthermore, taking into account the time spent to fix the ring, option A is considered with a high score than B. The score achieved in order to perform a good accessibility and maintenance is considered equal.

Finally, the scores are summed and it results option A as the design chosen. In the following sections, a stresses and displacement analysis is performed in order to assure the reliability of the concept chosen.

8. STRESS AND DISPLACEMENT ANALYSIS

In this chapter, a mechanical analysis of the principal stresses involved in the designed part of the test rig is developed. In order to perform this, the extension *Mechanica* from the application *Pro/Engineer Wildfire 5.0* has been used. The simulation is performed taking into consideration the elements of the clamping device as a unity, which means that each part is not simulated individually. Furthermore, the analysis is performed considering the behaviour of the material as linear-elastic. The clamping device of this analysis is modelled and displayed in the figure below. Its dimensions are presented in appendix D.

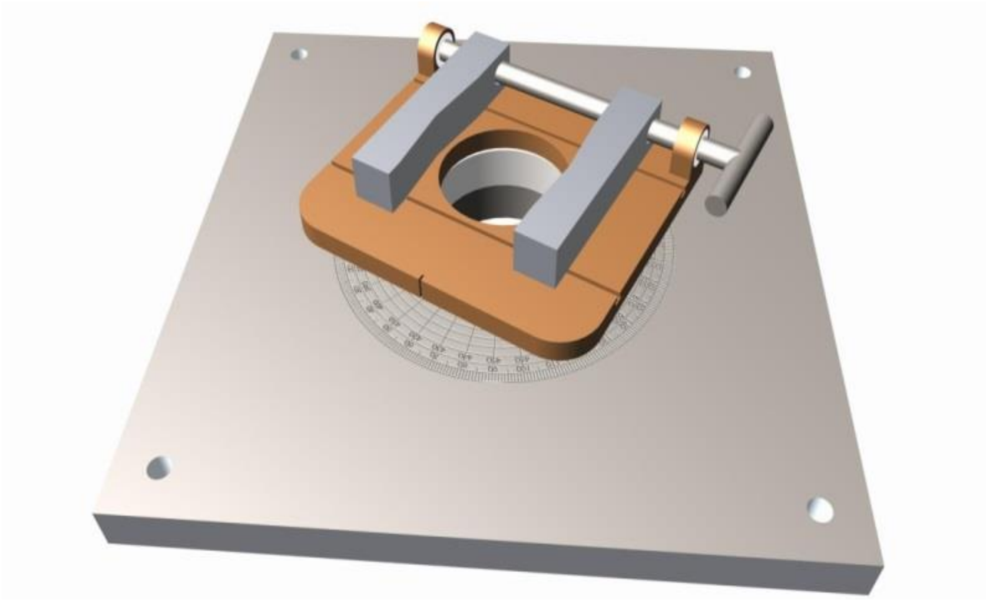


Figure 27: Perspective of the clamping device for clamping the ring.

8.1. CONSIDERATIONS

This stresses analysis is done so as to substantiate if the dimensions of the design chosen support the applied loads involved in the assembly process. In case that the results show that the model is not valid, the dimensions would have to be oversized and/or the selection of the material reconsidered. Hence, in order to start with the analysis, some considerations are required:

- The analysis is performed taking into consideration just the most conflictive region of the model, but the other parts will be also discussed later.

- Since the assembly process is performed at low and constant speed, the problem may be considered as static.
- The compressive force involved in the analysis is transmitted by the shaft and it is considered uniform with a value of 50 kN in the vertical direction.
- The selection of the material for the components of the clamping device is hardened steel AISI 8620. There is only a component, which is a bushing of 80mm diameter, composed by a different material. As the material of the bushing is a composition of steel as well as other layers of bronze and PTFE (Appendix D), specific material properties of it is not known. Thus, in order to simulate the problem, it is considered steel for the material of the bushing.

Table 6: Material inputs properties

	Hardened steel AISI 8620	**Steel**
Poisson's ratio (μ)	0.3	0.3
Young's modulus (E)	193 GPa	200 GPa
Tensile yield stress (B)	690 MPa	490 MPa
Tensile ultimate stress	925 MPa	690 MPa
Compressive ultimate stress	925 MPa	690 MPa

- The material is considered to have an elastic and isotropic behaviour.
- Since different sizes of rings may be installed into the clamping device, there are different contact areas to calculate the results. The most critical area will be the smallest one; due to the fact that all the stresses are directly proportional to the force applied, but indirectly proportional to the area where is applied (Equation 3). Thus, the more force and less area, the more stresses. Therefore, it is chosen the smallest ring for the simulation with an inner diameter of 60mm, an outer diameter of 68mm, and a thickness of 30 mm.
- Steel has the same behaviour both in traction and in compression. Therefore, its strain-stress graph is inverse (figure 28).

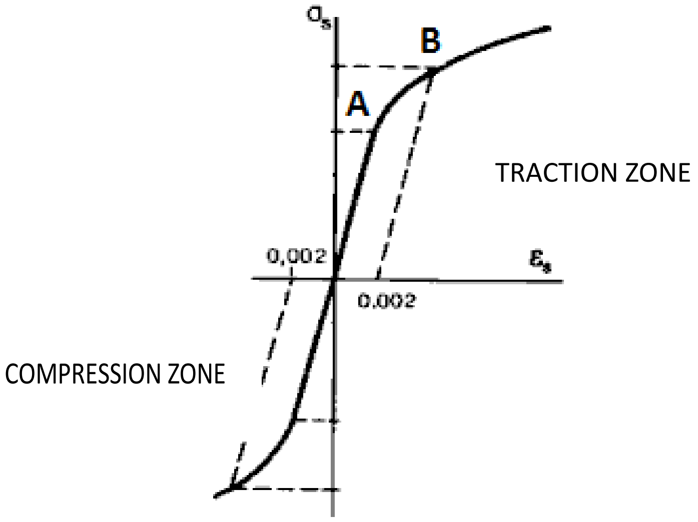


Figure 28: Tension-deformation (Archivo histórico, 2002).

The diagram displayed represents the usual behaviour of a ductile material. In the upper zone, materials subjected to traction are represented. On the other hand, materials subjected to compression are placed in the lower part of the diagram. Furthermore, the most representative points may be distinguished. Until point A, that is denoted as proportionality limit, the material works elastically. Point B is called elasticity limit, and represents the point that causes a permanent deformation of 0.2%. From point B, it is the fluency region, in which the deformation increases although the load is not increased. Finally, if the load continues being larger the material breaks.

8.1.1. Selection of the critical zone

The most critical region is the part which is directly involved in the assembly process. It is composed by the parts for which the shaft passes through and where the compressive force acts. It is a distributed force which is applied in *y*-direction and comprises the section of the ring. Figure 29 shows the force distribution.

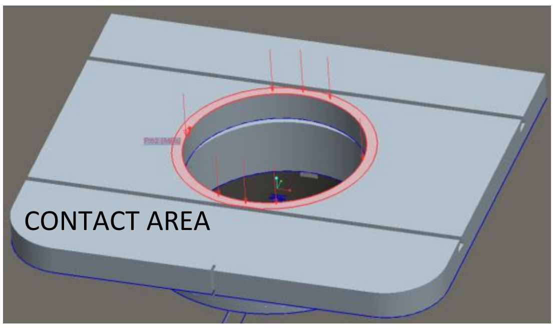


Figure 29: Distributed load applied in the clamping device.

In reality, as the teeth of the knurled regions of the shaft and the ring have a determinate slope, the compressive force may be decomposed in x and y direction as shows figure 30. This would be performed in this way if it is required to study the stresses in the ring. However, in the clamping device there is not any contact between the shaft the clamping device (Figure 31). The only force involved in the analysis is the compressive force along the y-axis with a value of 50 kN.

In case that there were any contact between the shaft and the clamping device, and some stresses were transmitted, both elements are symmetric and the sum of the x-component of the force would result zero. This possible contact could be due to an error performed by the operator or a non-proper manufacture of the components.

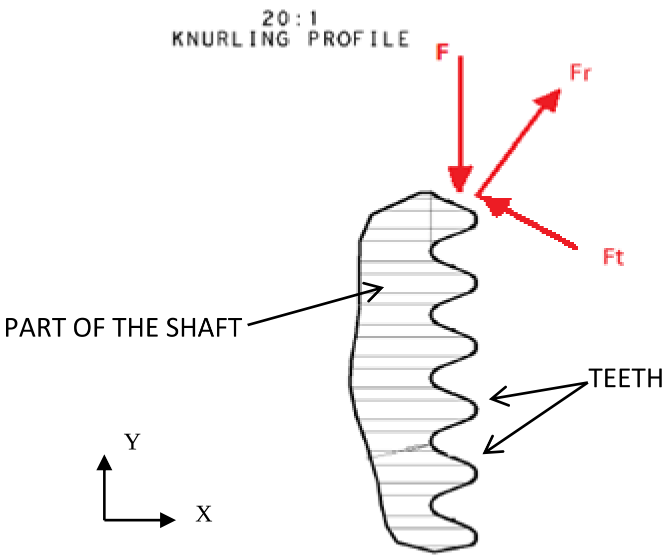


Figure 30: Forces involved in the knurled region when the shaft is in contact with the ring.

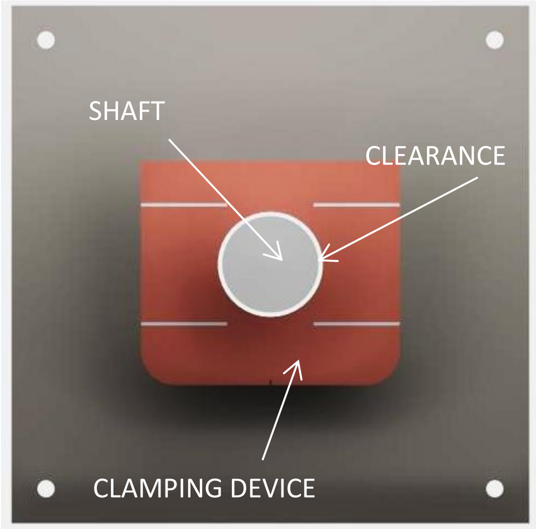


Figure 31: Top view of the clamping device with the shaft.

In figure 31, it can be observed that the shaft is not in contact with the inner surface of the clamping device. There is a small clearance to let the shaft pass through the clamping device without transmitting any normal stresses. To conclude, since there are certain components of the clamping device that are not involved in the analysis, they are removed. An exploded view of the elements involved is presented in figure 32.

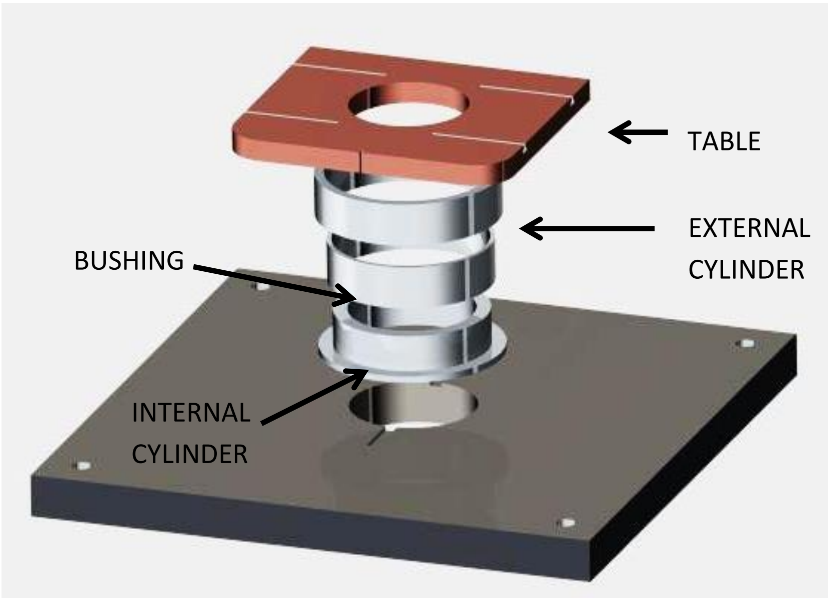


Figure 32: Exploded view of the components involved in the analysis.

8.1.2. Symmetry

A relevant aspect to take into consideration when a model is being analysed in simulation software is the symmetry. Perform this simplification in the execution of the model may reduce the time of simulation carried out. In the case of this study, since the components of the model were already built up as well as the simulation does not present many complications, simplifications due to symmetry is not used. Nonetheless, the symmetry present in the model is defined.

Since the model is composed by double-symmetrical elements, symmetry could be applied along *x* and *y* direction, and just a quarter of the model could be analysed. The only element which does not present the double-symmetry is the brownish table from figure 32.This element has round edges at two of its corners, thus, it would strictly present symmetry just according to one of its axis. Due to the fact that the rounds does not affect to the analysis, the double symmetry can be possible in this element too.

8.1.3. Boundary conditions and constraints

There is restriction of movement and rotation along *x*, *y* and *z* direction on the backside of the model as shows figure 33. In reality, the model is screwed to the test rig, therefore no translation neither rotation is allowed in any direction. In order to simulate this, some boundary conditions are required in the model.

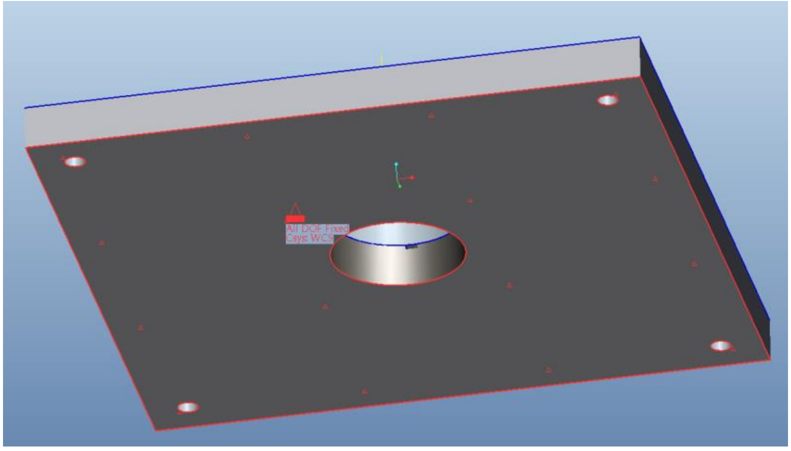


Figure 33: Boundary condition of the model

Furthermore, certain constraints between the elements involved in the analysis have to be defined. The external cylinder is soldered around its perimeter to the table as shows figure 32. Moreover, the internal cylinder is also soldered around its perimeter to the bottom. In both cases, no translation neither rotation is permitted. On the other hand, as the bushing concerned in the analysis is shorter than the external and internal cylinder, its upper part is not in contact with the brownish table, and, therefore, there is not any stresses transition through it. Thereupon, the bushing is only in contact with the cylinders.

8.2. STRESSES ACCORDING TO VON MISES

A stress analysis according to von Mises criterion is simulated in *Pro/Engineer* software in order to be able to compare the results obtained with the results from the analytical part. Moreover, the critical zones of the clamping device may be distinguished and explained.

In order to develop this simulation is taken into account the same conditions, considerations, and boundary conditions than in the analytical study. Figure 34displays the stresses in MPa supported by the model.

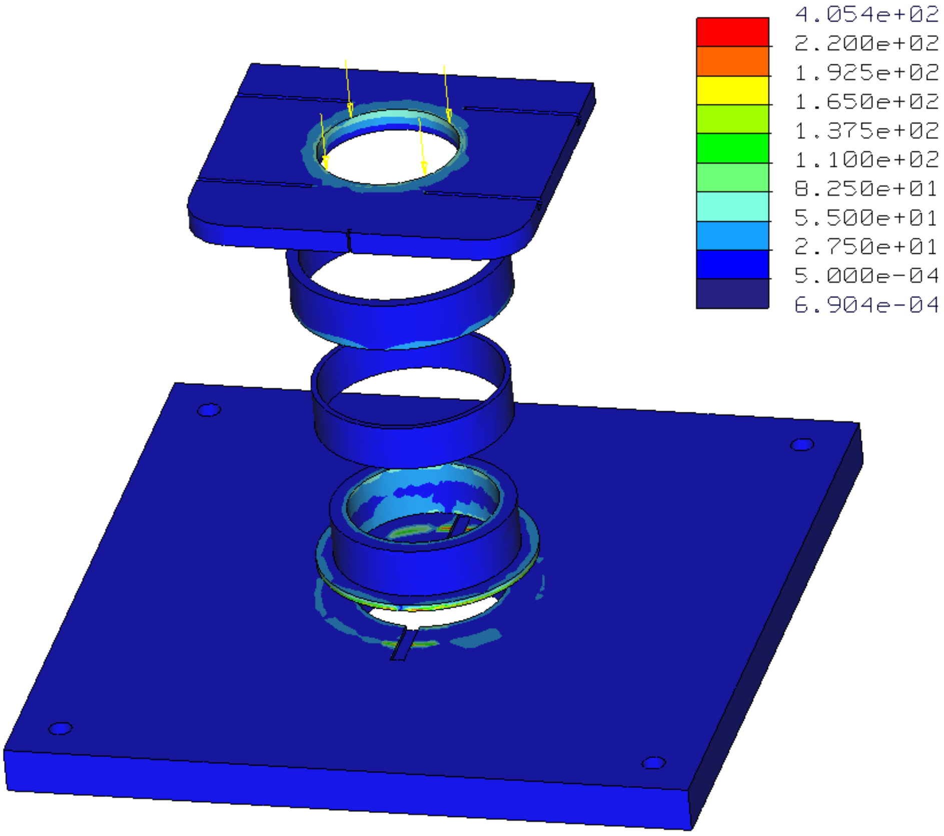


Figure 34: Exploded view of the model with the stresses present

It may be distinguished the lighter blue area form the figure shown above. With this, it is possible to ascertain that the stress supported in the pressing zone in the upper table, has a similar value that the analytical solution. Its approximate value is 55 MPa. Thus, the simulation is considered as valid.

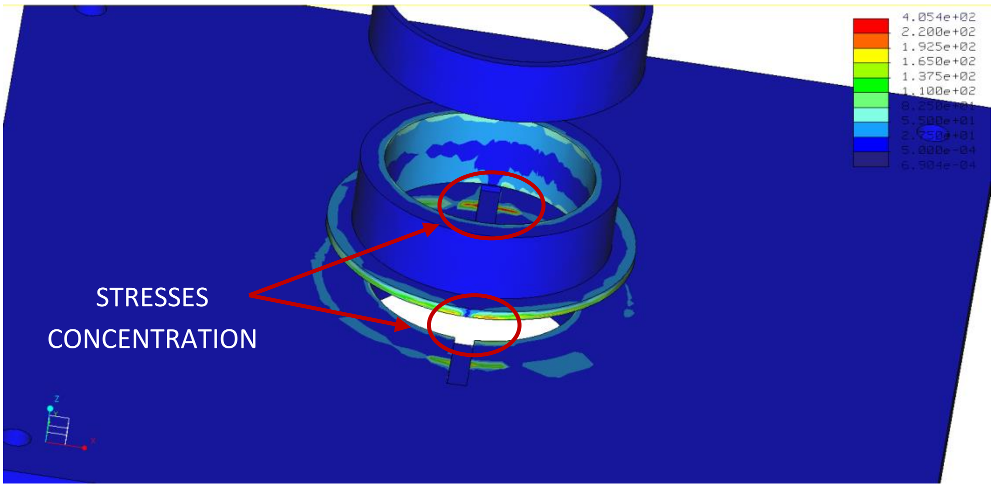


Figure 35: View with the most critical zones

The maximum stress presented when a compressive force of 50 kN is applied is 218MPa. As it is known, the tensile yield stress is 690 MPa, so the material does not yield. It is located in just two small areas signalized in figure 35, due to the fact that the perimeter of the cylinder is soldered, and stresses tend to concentrate there. In addition, due to the proximity of the T-slot rails, the stress increases because it tends to concentrate at their corners.

Finally, it can also be observed that any stress is transmitted to the bushing. Furthermore, the majority of the areas present a bluish colour, what means that there are not many areas with high stresses.

8.3. DISPLACEMENT

In the analysis of displacements realized, it is concluded that the most critical parts, which are painted in red, are the corners of the table and the perimeter of the hole where the compressive force is applied (Figure 36). The most relevant part is referred to the hole. There, the displacement goes downwards, with an approximate value of 9 µm. The result obtained guarantees the proper performance of the functions of the clamping device to assemble the work-pieces: there is not a large and irregular deformation in the hole, therefore, the perpendicularity as well as the entry of the shaft into the hole is assured.

The corners of the table are displaced upwards, and its maximum value is 11.4 µm. As the table is cantilevered, the more distance in cantilever has the more displacement it is produced. In the case of this study, the displacement is insignificant; it does not produce any effect into the table. If this value would be larger, it could cause some problems to the performance of the rails.

Table 7: Maximum displacements of the clamping device when a compressive force of 50 kN is applied

In the hole	9 µm
In the corners	11.4 µm

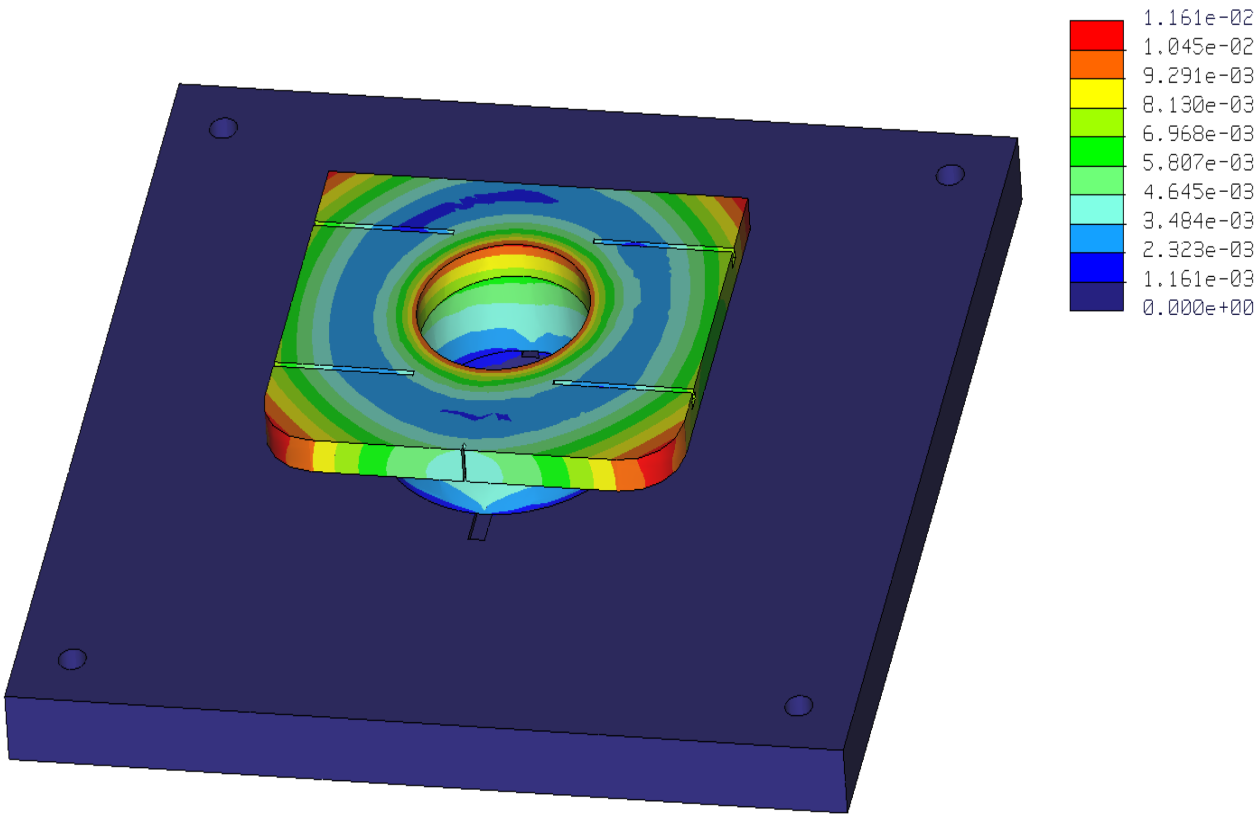


Figure 36: Displacement of the clamping device.

8.4. ANALYTICAL SOLUTION

Stress is defined as:

$$\sigma = \frac{F}{A} \quad [3]$$

Where F is the compressive force expressed in N and A is the cross-sectional area.

The cross-sectional area of the ring is given as:

$$A = \frac{\pi(\emptyset_{ext}^2 - \emptyset_{int}^2)}{4} \approx 800\ mm^2 \quad [4]$$

Where $\emptyset_{ext}$ and $\emptyset_{in}$ are the external and internal diameter of the ring, respectively. Therefore, by applying von Mises yield criterion (Sundström, 2010), it is obtained the expression which relates the equivalent yield stress with the yield strength:

$$\sigma_{vm} = \sqrt{\sigma_x^2 + 3\left(\tau_{xy}^2 + \tau_{xz}^2\right)} = \sqrt{\sigma^2 + 3\tau^2} \leq B \quad [5]$$

Where B is the point where the material starts to yield, whose value is 690MPa, and τ is defined as:

$$\tau = \frac{V}{A} \quad [6]$$

From equation 6, V is denoted as shear force. As the problem does not have any shear force applied, τ can be omitted, and therefore, the formula is as follows.

$$\sigma_{vm} = \sqrt{{\sigma_x}^2} \leq B$$

Thus,

$$\sigma = \frac{50\ 000\ N}{800\ mm^2} \approx 62\ MPa$$

The value of stress obtained shows that it does not reach the tensile limit of the material, so the designed model supports the loads without deforming. Therefore the model is considered as valid.

Knowing this, in order to calculate the displacement produced, according to Hooke´s law:

$$\sigma = E \cdot \varepsilon \tag{7}$$

Where, E is the Young's modulus with a value of 193 GPa. As the stress is already known, the strain ε is:

$$\varepsilon = \frac{\sigma}{E} = 3.2 \cdot 10^{-4} \tag{8}$$

It is also possible to calculate the strain. For this, according to Hooke's law:

$$\varepsilon = \frac{\Delta L}{L} \tag{9}$$

Where L is the original height of the model, whose value is 35mm, and ΔL is the variantion of longitude with respect to L. Thus,

$$\Delta L = \varepsilon L = 11.2\ \mu m \tag{10}$$

In connection with the functionality of the table, the result of the displacement produced does not affect to the assembly process based on knurling because the displacement is lower than the order of magnitude to the teeth of knurled region. Moreover, comparing the initial width of the table with the displaced one, it is shown that the percentage of variation is inappreciable.

$$\Delta L\ (\%) = \frac{L_0 - L}{L_0} \cdot 100 = 0.1\% \tag{11}$$

Where L_0 is the initial width of the table where the maximum displacement is produced. It has a value of 10mm.

8.5. RESULTS

The results obtained from the analytical calculation in addition to the simulation performed are exposed in table 9.

Table 8: Results obtained in the analyses performed in the clamping device

<table>
<tr><th></th><th>Analytical</th><th>Simulation</th></tr>
<tr><td rowspan="2">Stress according to von Mises</td><td rowspan="2">62 MPa</td><td>Maximum 405 MPa</td></tr>
<tr><td>In the perimeter of the hole 55MPa</td></tr>
<tr><td>Displacement</td><td>11.2 µm</td><td>9 µm</td></tr>
</table>

As it can be observed, there is an insignificant difference in the results obtained in the displacement. On the other hand, there is a considerable difference with respect to the results obtained for the maximum stress in the simulation and the analytical part. This may be due to the fact that in the simulation, the piece is bended because of the compressive force, and produces extra stresses in the model that, due to the results exposed, should be taken into consideration. Moreover, it is necessary to express that the maximum stress calculated in the simulation is not present in the area of the upper table. As it was said before, in this zone the stresses present a value of 55 MPa, a proximal value to the analytical solution. To conclude, in general, stresses are much lower through the entire model.

8.6. SIMULATION OF THE MOST CRITICAL SITUATION

A second simulation is performed in order to consider the most critical situation in the clamping device when the compressive force is applied. Due to a possible non-proper manufacture of the cylinders which forms the model, one of the cylinders may be longer that the other and all the stresses would have to be supported just by one of the cylinders. Thus, the simulation is carried out with the thinnest cylinder in order to be in the security side.

It is taken into account the same considerations exposed previously as well as the simplifications and boundary conditions which involves the elements present. Therefore, the results of the stresses and displacement are presented in figures 37, 38 and table 10.

Table 9: Results for the second simulation of the clamping device

Stresses according to von Mises	*580 MPa*
Displacement	*189 µm*

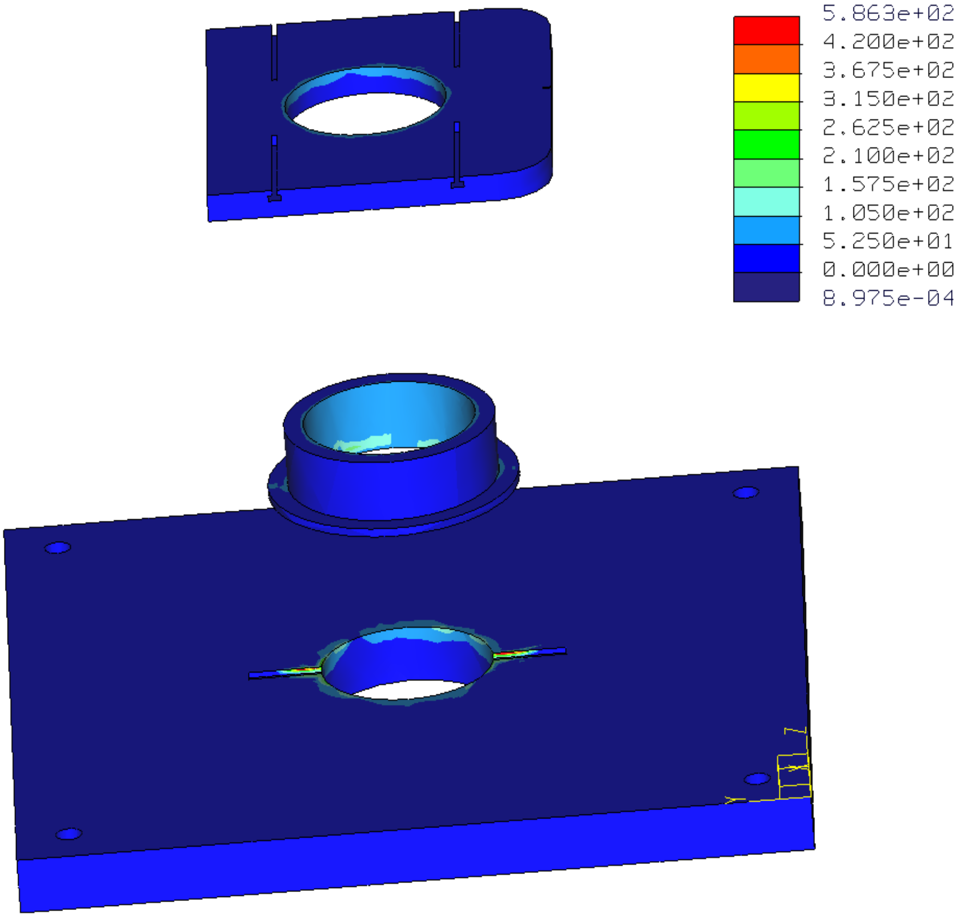


Figure 37: Exploded view of the stresses according to von Mises for the second simulation of the clamping device

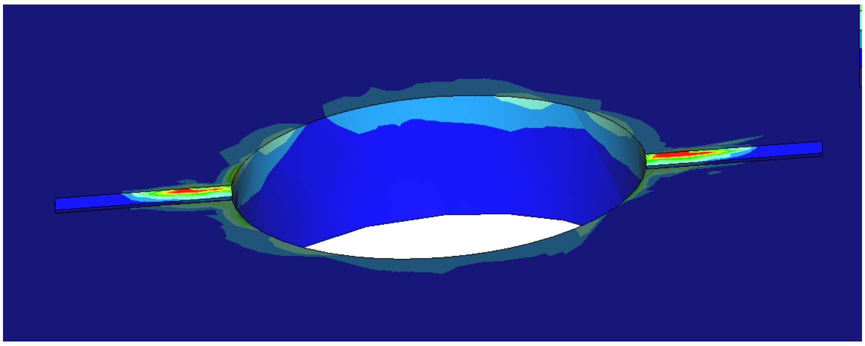


Figure 38: Location of the highest stresses in the clamping device

In this case, the maximum stress has a value of 580MPa, and is situated in the same place as in the first simulation (See figure 38). Although the value of the stresses has increased, they are still in a value under the yield point of 690 MPa. Thereby, any permanent deformation in the clamping device is not produced. Thus, it is not necessary oversize any component neither re-chose the material, so the clamping device is supposed to operates properly its functions established.

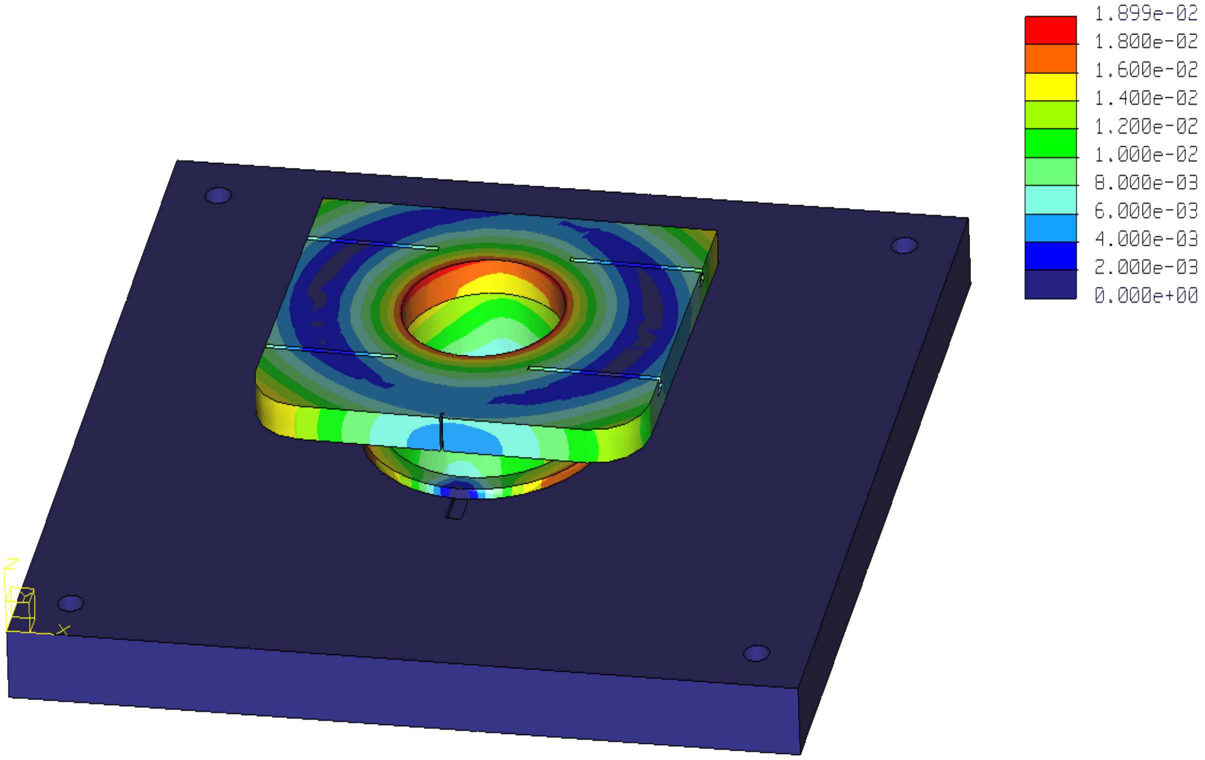


Figure 39: Displacement of the clamping device for the second simulation

In this case, the displacement has increased up to 0.189 mm, but this value is still insignificant to produce any effect in the piece.

8.7. DISCUSSION OF THE OTHER COMPONENTS

The elements which have been removed also support efforts, but they are not considered in this analysis due to the fact that they are smaller, and it is considered that if the clamping device supports the highest stresses, the rest of the parts which are subjected to other smaller forces will also support them.

In the case of the jaws which are placed in the brownish table as shows figure 40, each jaw would have to support the *x*-component of the compressive force decomposed in the knurled region of the ring. This force would be placed in the contact zone specified in the figure. Furthermore, as both jaws are connected with a threaded shaft, in the threaded area would be certain stresses concentrations transmitted from each jaw. The application of this force would also produce a moment in the area where the jaws are clamped cf. Figure 40, producing certain stresses in the rails.

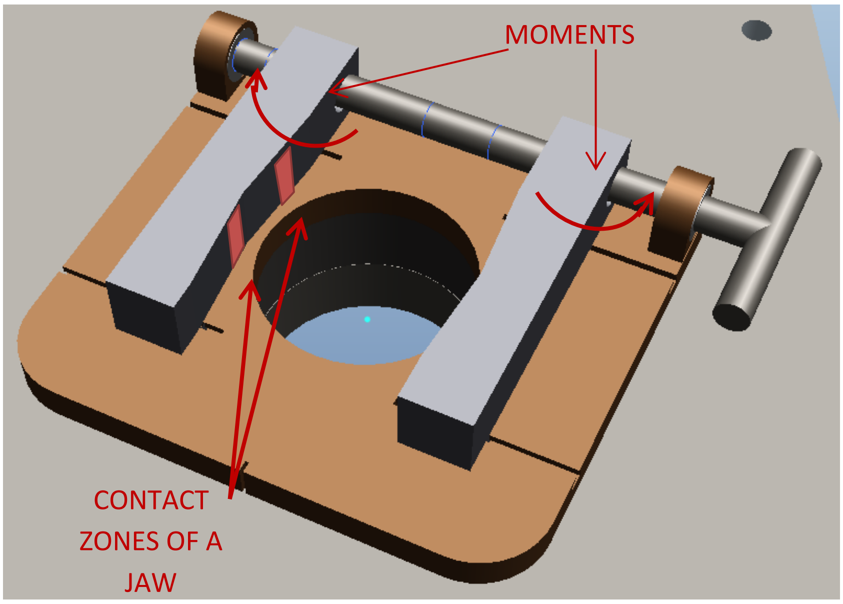


Figure 40: Contact zones and moments produced in the jaws of the clamping device

On the other hand, the stresses present in the braces placed in the lower part of the clamping device even lower that in the jaws. They would not have to support the compression force, neither its x-decomposition due to the knurled region.

The function of the braces consists of restringing the rotation of the cylinders of the clamping device when the assembly is in being performed. Besides, as the element to fix is always the same (in this case it would be the external cylinder), the contact area would be the whole contact surface.

In this case, it would be present a friction force, tangent to the cylinder and opposite to the movement performed. Figure 41 presents the contact surface and the elements involved.

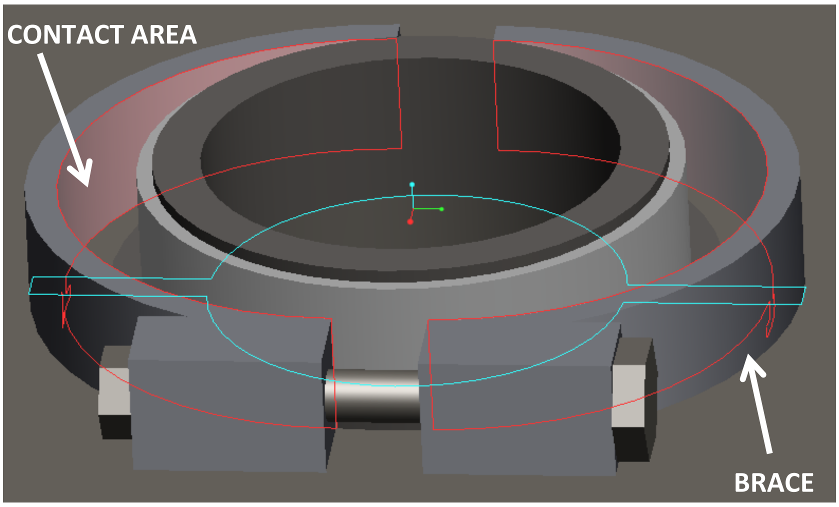


Figure 41: Contact areas of the braces of the clamping device.

9. FINAL CONCEPT

The solution of the final design of the test rig to assemble is exposed in this chapter. According to the division done in section 4, the test rig was divided into three parts; therefore, the solution includes the characteristics of each part in addition to its principle of operation. A summary with the principal characteristics of each part is done in Appendix C, where their necessities and qualities are presented.

9.1. ELECTRO-MECHANICAL TEST RIG

The solution for the design of the test rig is accomplished with the alternatives arisen from the market research performed through this paper as well as its subsequent evaluation. Then, the selected solution is the *5960 Dual Column Table Frame* from the company *Instron*. The design is composed by several elements, shown in figure 42. The principal characteristics are defined in table 10.

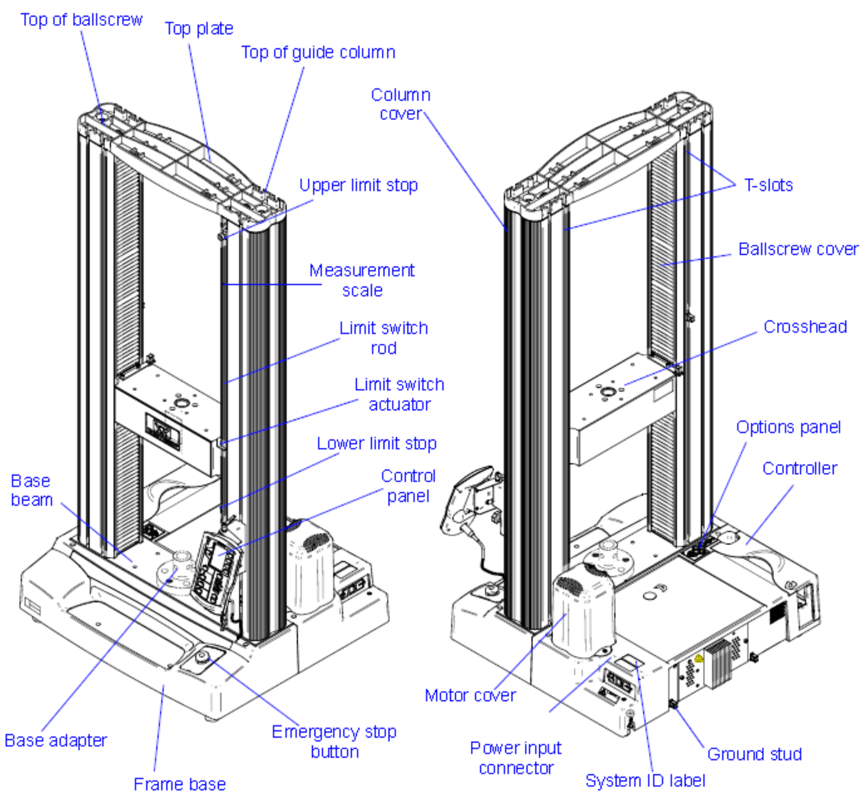


Figure 42: Front and rear view of the electro-mechanical test rig (Instron, 2013)

Table 10: Testing system components for 5960 Dual Column Table Frame

Component	Description
Load frame with integral controller	It comprises a base, two columns, a moving crosshead, and a top plate. Its high stiffness supports the structure against the testing forces. Each column comprises a guide column and a ball-screw. The crosshead is mounted on both the guide column and the ball-screw. Rotation of the ball-screw drives the crosshead up or down while the guide column provides stability.
Load string	Comprises all of the components that are installed between the moving crosshead and the load frame base. It involves a load cell, a set of grips, any adapters that are required to connect the components, and the work-piece to be tested. The load cell is mounted on the crosshead, and the grips on the load cell.
Grips for clamping the work-pieces	The grips secure the specimen and when a test is started, the crosshead moves up or down applying a tensile or compressive load to the specimen. Then, the load cell converts this load into an electrical signal that the software measures and displays.
A test-table	It is mounted to attach and place other specimens.
Controller	The hardware that controls the frame and any ancillary equipment connected to the testing system. The controller panel contains all the connectors for load cells, extensometers and any other sensors that are required for testing.
Control panel	The hardware panel, mounted on the side of the load frame that lets you performs some of the software functions directly at the frame.
Instron approved computer system with InstronBluehill® software	The software controls the testing system, running tests and analysing test data to perform test results.

All these elements are bought and attached from Instron supplier, as well as its material properties, operation and principal characteristics (Instron, 2013). In figure 42, the components of the machinery are exposed.

9.1.1. Dimensions

The most suitable model in order to perform the tests to study the assembly process is the model 5967, which is a sub-category from the *5960 Dual Colum Table Frame* (Instron, 2013). It is characterized by possess an extra height and wide for the work-pieces. Its main dimensions are presented in table 11 and figure 43.

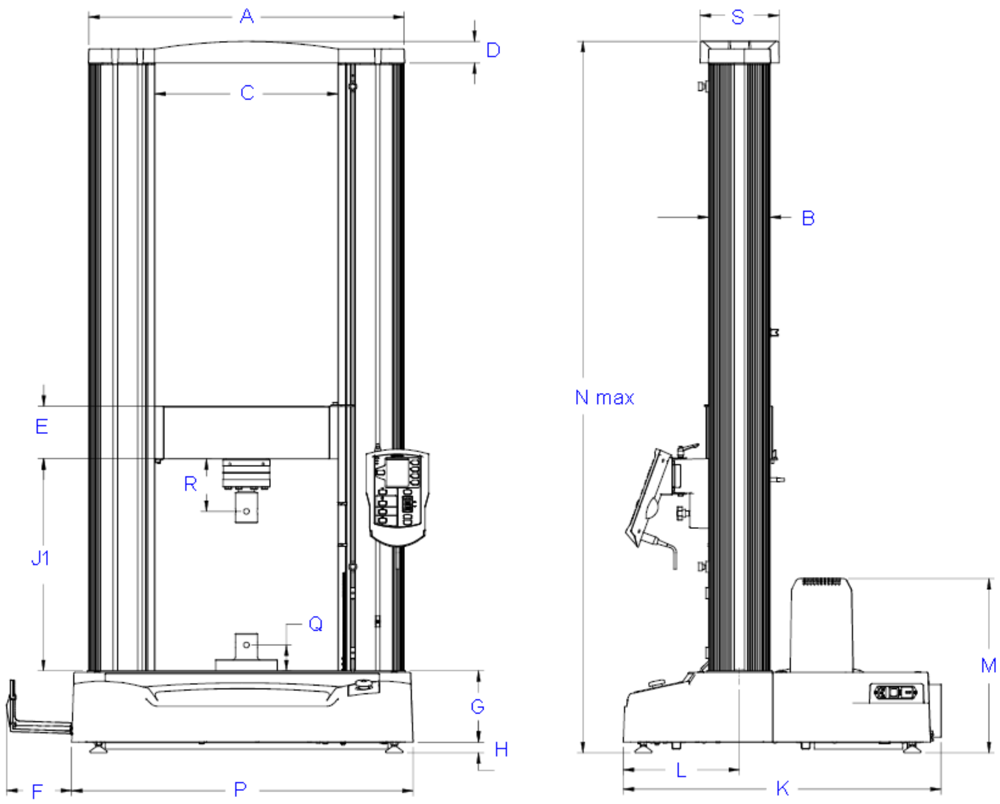


Figure 43: Principal Dimensions of the Model (Instron, 2013)

Table 11: Principal characteristics of the model

Model 5969 with an extra weight and wide configuration		
N max	Overall height	2120 mm
C	Horizontal test daylight	946 mm
J1	Cross head position Minimum Maximum	 67 mm 1697 mm
P	Overall width	1278 mm

9.1.2. Specifications

With the selection of the machinery, it is possible to perform the entire functions and objectives required for the Company. These are attached in table 12.

Table 12: Other specifications for the model 5969 chosen

Weight load frame	453 kg
Accuracy in the measurement of the load	± 0.5 N (Model Instron 2580 Series load cell)
Position accuracy	± 0.01 mm
Load capacity	50 kN
Velocity range	0.001 - 3000 mm/min
Control panel	Customizable
Controllable force	Available
Controllable stroke	Available

9.2. SHAFT CLAMPING TOOL

In this case, the solution for the design of the device responsible of clamping the shaft is also accomplished with the alternatives arisen from the market research performed previously. The final selection is the *Pneumatic Wedge Action Grips* from the company *Instron (Figure 44)*. They are side-action grips with a pneumatic principle of operation. The clamping force is controlled by adjusting the inner pressure which remains constant during the test.

Figure 44: Pneumatic Wedge Action Grips (Instron, 2013)

The grips are also characterised by its robust design as well as its quick and easy operation, what improves its usability and productivity in comparison with other types of gripping devices (Instron, 2013). Its main characteristics are presented in table 13 (Instron, 2013).

Table 13: Specifications for Pneumatic Wedge Action Grip

Model number 2716-110 (Customizable)	
Capacity	100 kN
Weight	52 kg
Maximum Operating Pressure	8.5 bar
Temperature Range	5 ºC to 65 ºC
Maximum width of Grip	300 mm
Specimen thickness	50.8 mm. As a larger diameter is required, the grip is redesigned by the Company to be able to clamp a 60mm diameter
Flexible clamping	It is possible to clamp round and flat surfaces

9.3. RING CLAMPING TOOL

The solution for the clamping tool to fix the ring is simulated in *Pro/Engineer*. It is designed taking into account the specifications of the Company, other aims established through this paper and the design method used. The final result is shown in the figure exposed below and its main characteristics are presented in table 14.

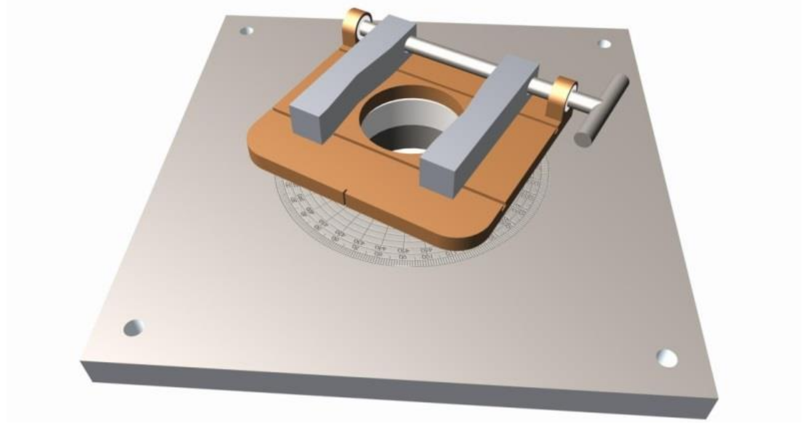


Figure 45: Ring clamping tool.

Table 14: Specifications for the clamping device to fix a ring

Specification	Description
Perform a quick and easy installation of the ring	The operator uses just one hand to clamp the ring. The process is controlled manually with a handle. The ring is clamped with the help of two jaws which are controlled by a thread worm.
Diminish operator errors	
Easy maintenance	All the elements are previously chosen to perform an easy and minimum maintenance.
Self-centred	The jaws are controlled by the same axle which is controlled by the operator .Therefore, both jaws moves at the same time, performing a more accurate fixation of the ring.
Flexible clamping	It is possible to assembly different sizes and types of rings.
Standard components	It is chosen as many standard components as possible. Pieces 2, 11, 12, 13. (Figure 47). The rest are easily manufactured.
Control the orientation of the work-piece (Figure 46)	It is controlled manually. Its maximum error is of 1°. Good accessibility to the measuring system

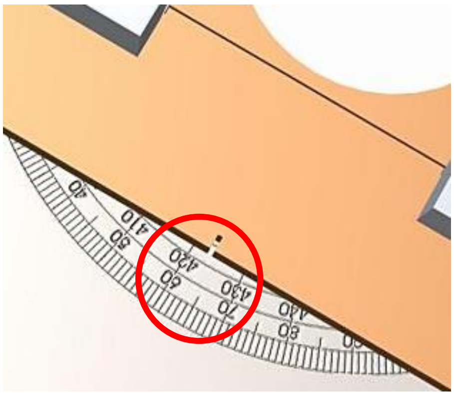


Figure 46: View to see how to control of the orientation of the ring.

Drawings with dimensions of each component and an explode drawing are attached in Appendix D. These ones were created in A3 format as original size, but in this report they are attached with a smaller format; thus the scales of the drawings are not in accordance with their dimensions.

9.3.1. Materials and components

Material and components are needed to be defined to this design part. To obtain a better knowledge, figure 47 shows an exploded view where it is possible to identify each part of the device. In the figure, the components are numbered in order to define and denote each component. All the components except elements 3 and 13 are made from stainless steel because of its easy manufacture and good resistance against corrosion and oxidation (Steel Manager Limited, 2006), but different types of steel are chosen depending on the finality of each element. Table 16 shows the denotation mentioned in addition to the material chosen.

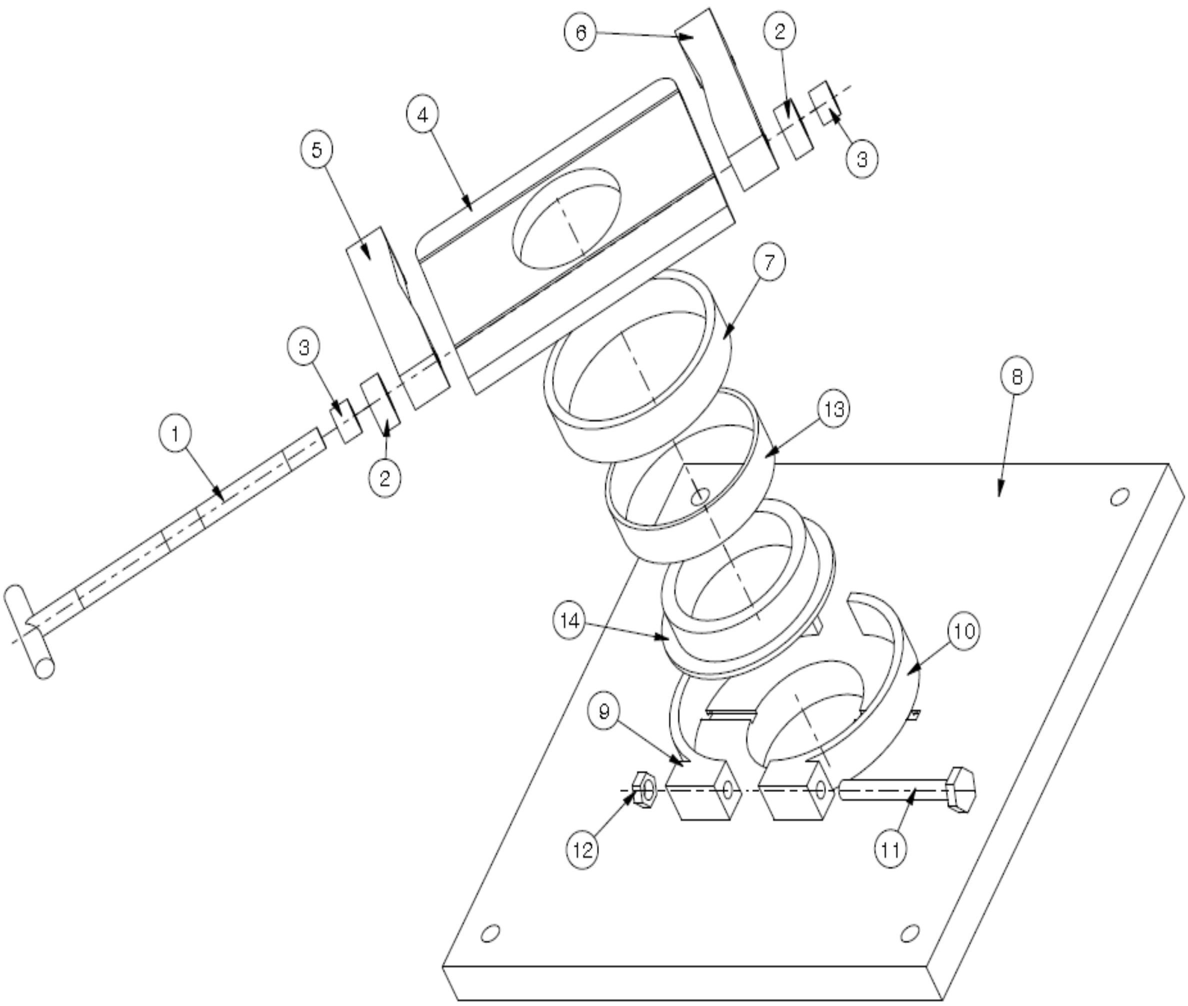


Figure 47: Exploded view of the ring clamping tool.

Table 15: Numeration of the components of the ring clamping tool

Nr.	Component	Designation	Quantity	Material
1	Double Thread Worm		1	AISI A-2 Tool Steel
2	Bracket		2	Hardened Steel AISI 8620
3	Bushing Ø10 mm	PBN101610 M1	2	Solid Bronze
4	Board I		1	Hardened Steel AISI 8620
5	Jaw I		1	Hardened Steel AISI 8620
6	Jaw II		1	Hardened Steel AISI 8620
7	Cylinder II		1	Hardened Steel AISI 8620
8	Board II		1	Hardened Steel AISI 8620
9	Brace I		1	Hardened Steel AISI 8620
10	Brace II		1	Hardened Steel AISI 8620
11	Screw M8 x 1.5 x 70		1	AISI A-2 Tool Steel
12	Nut M8 x 1.5		1	AISI A-2 Tool Steel
13	Bushing Ø80 mm	PCM808520B	1	PTFE Composite
14	Cylinder I		1	Hardened Steel AISI 8620

It can be possible to present the material properties for each component in Appendix E in addition checking the properties of the bushing chosen in Appendix F.

9.3.2. Attachment

Hence, it is only required to define the fixation of the ring clamping mechanism for the test rig. In order to perform this, and taking advantage of the drilling predefined in the test table from *Instron*, the clamping device is fastened with screws. Figure 48 shows the attachment in order to achieve the joint.

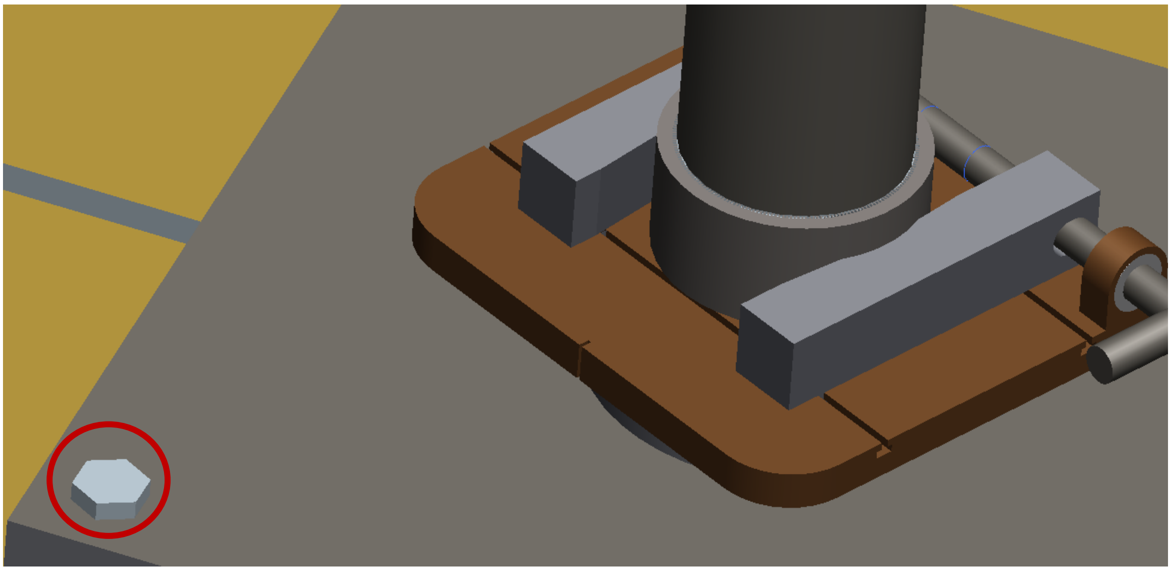


Figure 48: Attachment of the ring clamping tool to the electro-mechanical test-rig.

Moreover, the fixation of the components which form the clamping device is required to be defined.

There are two plain bearings installed in the clamping, SKF (2013). They are denoted as bushings, and are the elements number 3 and 13 (Figure 47). They are installed in accordance with the specifications of the supplier by applying a pressing force in order to assemble the bushing with its contact components.

Due to the necessity of fixing diverse components without any fastener, these elements are soldered with continuous corner welding. According to the figure 47, the elements concerned are the number 2, 4, 7, 8 and 14. The elements 2 and 7 are brazed to the element 4 and element 8 is soldered to the element 14. Figure 49, shows some welded parts.

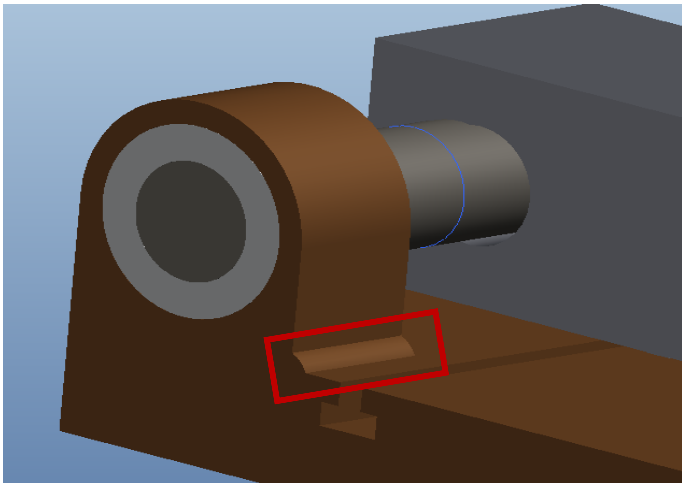


Figure 49: Welded parts

Elements 5, 6, 11 and 12 are jaws and braces which are directed by T-slot guide rails. In figure 50, the elements and their connections are shown.

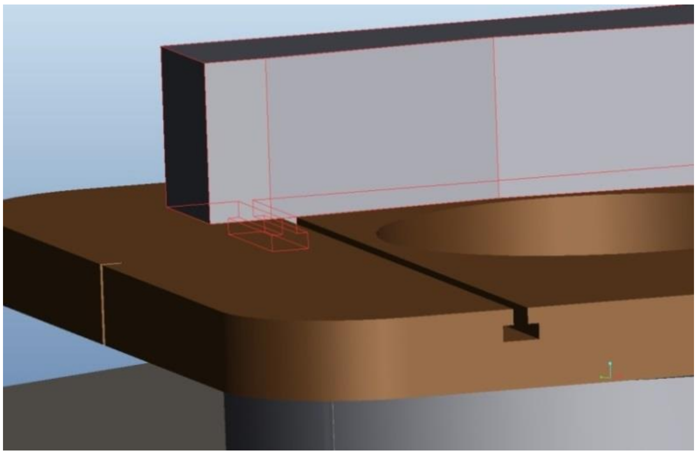


Figure 50: T-slot guide rails of the clamping tool for the ring.

9.4. FINAL 3D-MODEL

In this chapter, the final model is presented. The 3D model from the figure exposed below, is simulated in *Pro/Engineer* software. The components chosen from catalogues were simplified and drawn in order to facilitate an overview of the final solution for the test rig.

Figure 51: Final design for the test rig to assemble. Left with the shaft, right without the shaft

The part are drawn keeping the proportion between them, therefore, the scale was taken into account to create the model.

9.5. PRINCIPLE OF OPERATION

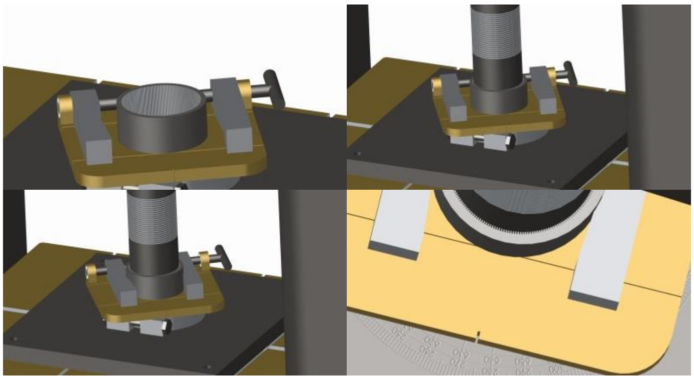
Once the final solution of the test rig is achieved, its principle of operation is exposed in order to have a better knowledge about it. Figures 52-54 shows the principle.

1. The work tables are located in the correct position. Depending of the position where the ring going to be joint to the shaft

2. The shaft is clamped in the test rig

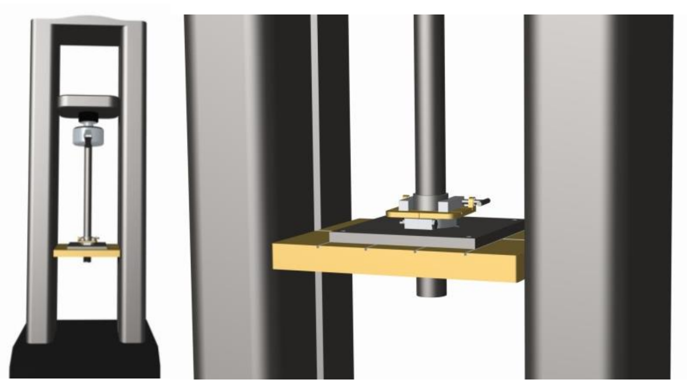
3. Before clamping the shaft, this one is knurled on the outer surface

Figure 52: Operation part I

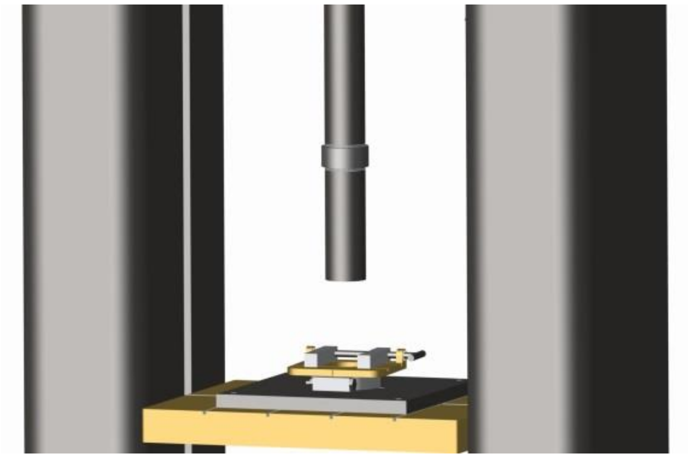


4. The ring is located in the clamping device of the test rig
5. It is used the own shaft to orientate axially the ring on the hole
6. The ring is clamped using the brackets
7. It is chosen the angle of orientation of the ring

Figure 53: Operation part II



8. It is applied the pressing force to accomplish the assembly. This is the most important movement of the test rig due to the necessity of develop a perpendicular displacement without clearance between pieces



9. The knurled region creates the joint between them, PKF method

10. The shaft is returned to the original position with the ring assembled

Figure 54: Operation part III

The work piece assembled is removed to the clamping device of the shaft, and the work piece is obtained, figure below.

Figure 55: Assembled work-piece

To clamping more rings, it is needed to remove the element, to make other knurled region in the shaft, and then it is executed again the process of assembly before, with a new ring.

10. DISCUSSION

The discussion of the results obtained in this paper is focused in an evaluation of the test rig designed in addition to a consideration of its sustainable development.

10.1. EVALUATION OF THE TEST RIG

According to the results, the design is characterized by:

- Its simplicity. The test rig is designed with standardize components, in order to obtain a quick manufacture.
- Its simple handling.
- Its reliable operation is considered adequate in order to develop its purpose.

On the other hand, there are some aspects which should be taken into consideration in order to improve the design:

- The part of the ring clamping device responsible of blocking the rotation of it when the assembly process takes place could be improved. The elements concerned are called braces, and they are the elements number 9 and 10 from figure 47. These elements work with the friction originated between them and their contact elements. As alternative, it could be installed an element which fixes directly the involved elements and do not let rotate them.
- The selected solution for placing the ring coaxially with the shaft could be improved. The procedure consists of introducing the shaft through the ring in order to clamp the ring aligned with the shaft. However, in order to improve this, it could be installed in the clamping device of the ring a component which helps to perform the alignment.

10.2. SUSTAINABLE DEVELOPMENT

According to World Commission on Environment and Development (WCED), sustainable development is defined as the development that *"meets the needs of the present without compromising the ability of future generation to meet their own needs".* The sustainability is also a point to discuss in this thesis. It involves the economical, environmental, and social aspect. In the case of this study, the social aspect is not considered in the discussion due to its minor influence.

On the one hand, costs can be discussed in two ways: Costs related with the manufacture and installation of the test rig and the possible saving of cost by implementing the PFK method with respect to the lathing method.

The cost related with the manufacture of the test rig depends on the price of each part of the machinery. These are established by Instron and the manufacturing costs which involve the clamping for the ring. This cost for manufacturing depends on the materials chosen, the manufacturing process and labour required. Materials were chosen taking into consideration the analysis of stresses performed in section 8 with the finality of supporting the compressive force applied.

With regard to the study of the novel assembly method, whether this test rig is manufactured and the PFK method is developed, the cost of the process of creating the final work-piece is improved in relation with the traditional lathing process. This is due to the fact that a considerable quantity of material is saved, because of the turnings generated with the traditional method, and the possibility of using a hollow shaft.

It is reminded that this test rig has the purpose of making tests to study the assembly process. Therefore, once considered that the machinery is feasible, the process will be implemented in the assembly line of the Company. Thus, this implementation can be economically compared with the actual one. The principal aspect to take into consideration is the processing time. With the novel assembly method (PFK), the required time to manufacture a work-piece per unit of time is lower than with the actual manufacturing process. Thus the productivity increases, allowing create more pieces per unit of time.

On the other hand, the implementation of the PFK method could influence in the environmental aspect. With the novel assembly method, the shaft could be hollowed, thus it would be needed less raw material. Moreover, turnings are not originated with this process. Therefore, it would be decreased the use of the steel recourses and less pollution would be generated.

Another environmental aspect to take into consideration is the selection of the material of the element designed in this project. The materials chosen were different types of steel. These can be recycled and reutilized in order to produce new products in the future. Furthermore, its components can be easily separated in order to recycle their parts.

The design presented through this project was simulated in CAD software in order to visualize it as well as test it without making any real prototype, being green with the environment.

11. CONCLUSSIONS

From the work performed during this Bachelor Degree Project it is possible to conclude that the main objective has been satisfied. The results obtained are in accordance with the aims and specifications established through this paper, and they can be implemented in order to contribute with the study of the novel assembly process in which knurling takes part.

The principal aim why this thesis was developed, detailed at the beginning of this paper, is focused in design of a test rig to assemble work-pieces. In order to develop it, a rational design methodology was applied. Clarifications of the objectives and functions as well as a market research were performed previously. Consequently, the test rig is divided into three parts. It is concluded that by dividing the problem into sub-problems in order to find sub-solutions it is possible to achieve the final solution successfully.

An important aspect which was taken into consideration in order to fulfil another purpose established by the Company was providing to the design simplicity and standards parts. This objective was entirely achieved performing a deep research and selecting product from catalogues which satisfies the specifications of design. In this present case, a test rig and grips for clamping were chosen. There was just one part of the machinery which has been designed completely. But even in this case, as many standards components as possible were installed.

Thus, the final concept of the model was developed. In order to generate a higher level of reliability in the results obtained, certain simulations and calculations were performed. The results concluded that the concept is able to withstand the forces involved in assembly process; therefore, the model is valid.

12. FUTURE WORK

There are diverse possibilities of continuing developing the result obtained in the design of the test rig; however, there are also potential studies which can be started from the realization of this project.

In short-term:

With the design of the clamping device concluded, the following step would be manufacturing a prototype. The other two parts of the test rig should be bought in order to install the entire test rig.

An ergonomic studio could be performed in order to optimize the relation between machine and operator.

The process of testing with the test rig could start, and the work-piece could be assembled. Firstly, the process would be carried out with one ring and then with several rings installed in the same shaft. Furthermore, is could be tested different sizes and shapes of rings. With this, the Company would obtain preliminary results in the study of the novel joining method.

The parameters involved in the knurling process could be studied in depth. A finite element analysis could be carried out in order to provide information about how the forces are distributed on the knurling region as well as other factors which take part in the assembly process. If these parameters are known, the test rig would perform a more accurate operation.

In a long-range plan:

The Company attempt to change the manufacturing process of one of their work-pieces. Thus, if this process is implemented in an assembly line, the efficacy in the production would be improved, saving energy, time, materials and costs. Therefore, for the future, this machinery should be improved and implemented in the production line of the Company.

As improvement, consider the possibility of performing the knurling process in the same machinery. Until now, knurling was done in a lathe and thereafter, the assembly process took place in the machinery of this study. As a result, the process would be faster and costs would be reduced.

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14. APPENDIXES

A. TIME PLANING AND WORK BREAKDOWN STRUCTURE

To achieve this thesis efficiently, a Work Breakdown Structure is performed. It is a decomposition of the activities of the project into smaller ones in order to organize and define the management of the project. Figure 56 exposes the WBS diagram defined for this paper:

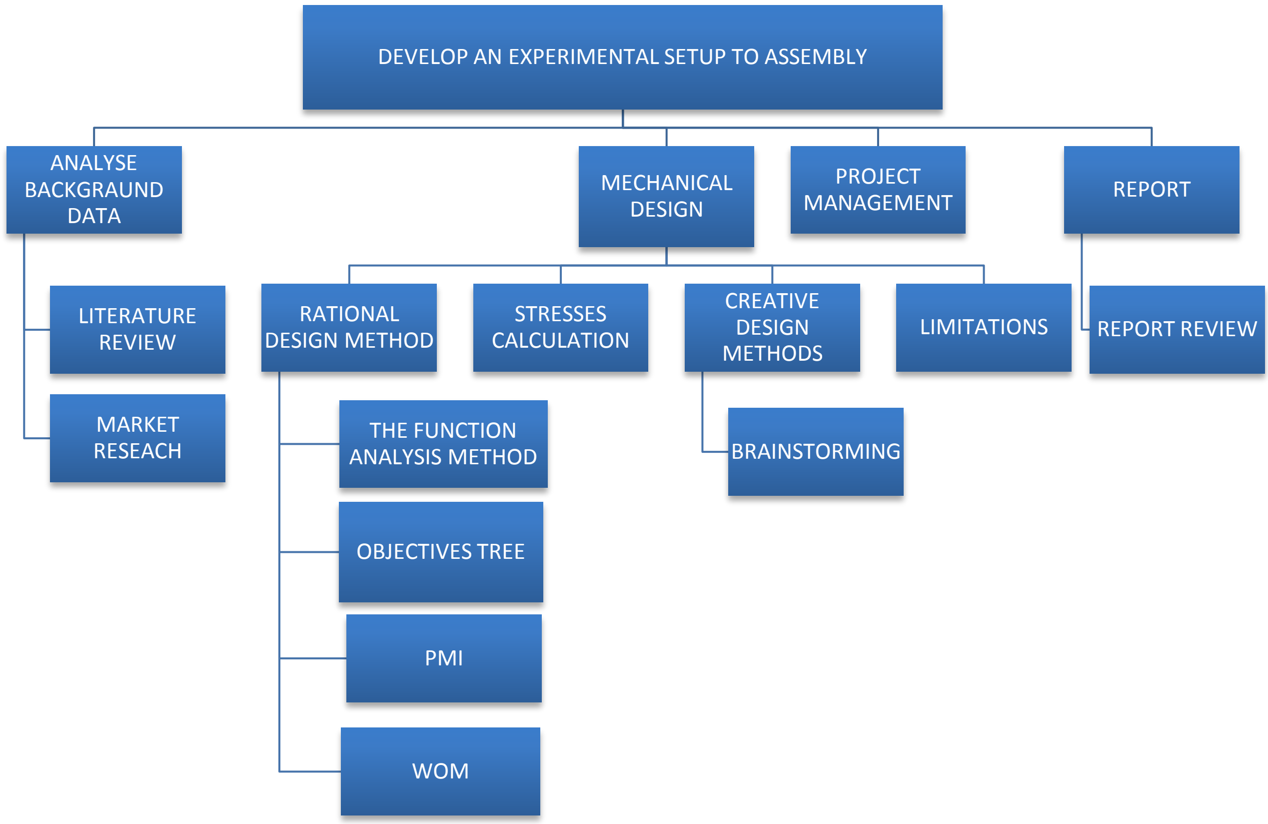


Figure 56: WBS diagram

Furthermore, a time planning is performed to schedule the activities of the project. It illustrates the start and finish dates, the duration of each task and the dependency of each activity with respect to the others. Figure 57 shows the Gantt diagram which plans the management of the project.

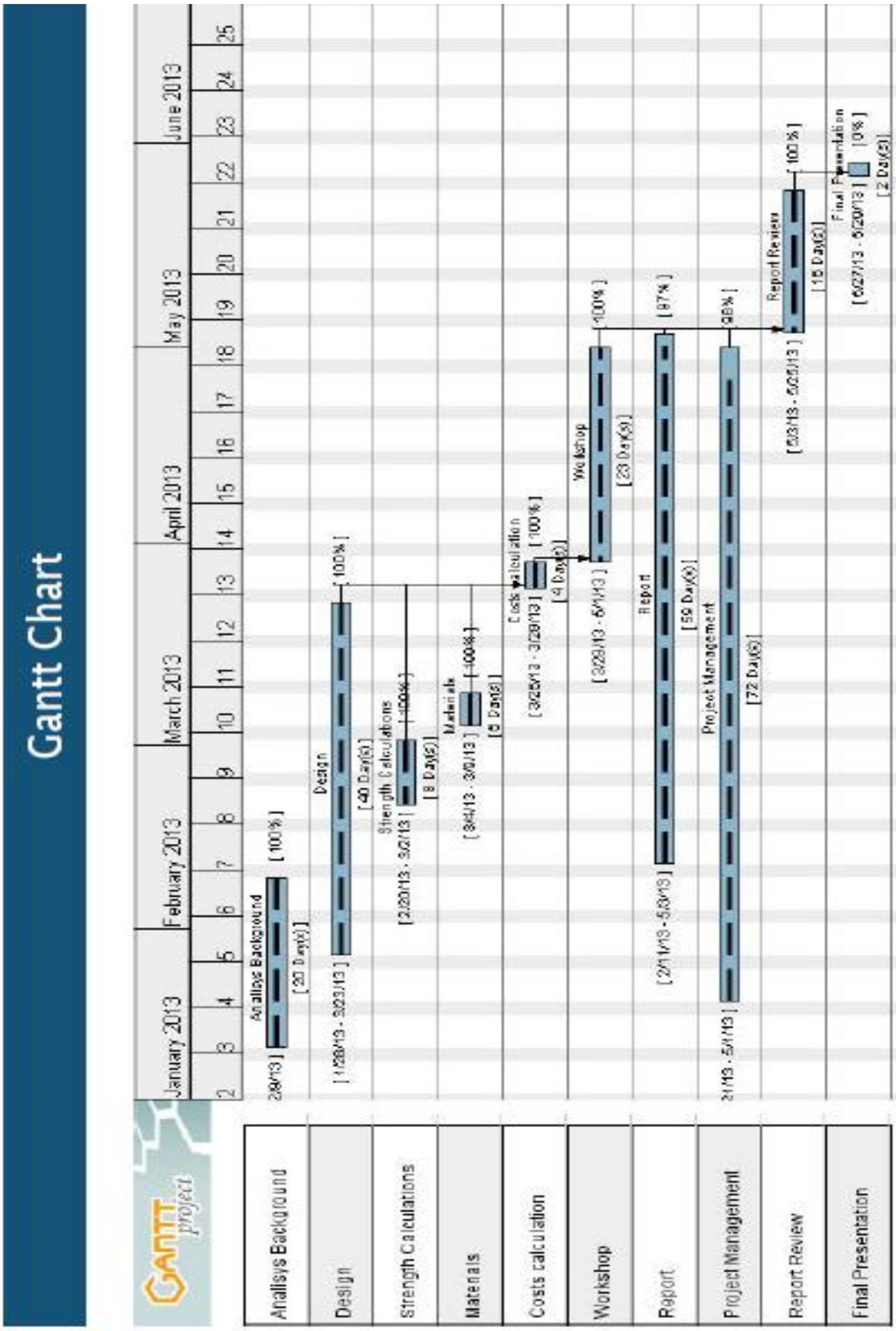


Figure 57: Figure 58: Gantt diagram

As it can be observed, a black dashed line it is drawn in the chart. This express the progress achieved of each activity.

B. SIMPLE CHART OF EVALUATING CONCEPTS

These tables are made in order to valuate easily every characteristic of each concept generated in section 7.3. Table 17is developed with values between 0 and 1. The members from a same level are located in the first row and column. Then, each member of the column is compared with the ones of the row, allocating 0 if the first member is less important than the second and if it is more important, the value 1 is taken. In order to facilitate the relation among sub-objectives, these are designed with capital letters.

Level 1:

- Develop a reliable operation → A
- Have high safety → B
- Have simple design → C
- Perform a good operation → D

Level 2:

- Control → E
- Assembly different rings → F
- Perform optimal fit → G

Once simplified the sub-objectives, it is realized the simple chart for each group as displays table 17. Group 1 is formed by reliable operation, control, high safety and assembly different ring; group 2 by simple design, perform optimal fit and good operation.

Table 16: Simple chart to value the sub-functions from level 1 of the clamping device

Level 1	A	B	C	D	**TOTAL**
A	-	1	1	1	3
B	0	-	1	0	1
C	0	0	-	1	1
D	0	1	0	-	1

Table 17: Simple chart to value the sub-functions from level 2 of the clamping device

Level 2	E	F	G	**TOTAL**
E	-	1	1	2
F	0	-	1	1
G	0	0	-	0

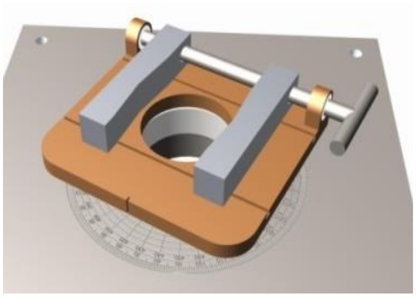
The total sum of each row is located in the last column. It denotes the value that has the sub-function inside its group. Then, it is weighed each sub-function in a 0-1 scale. Thus the score to each one is showed in table 19.

Table 18: Score for each group of functions of the test rig.

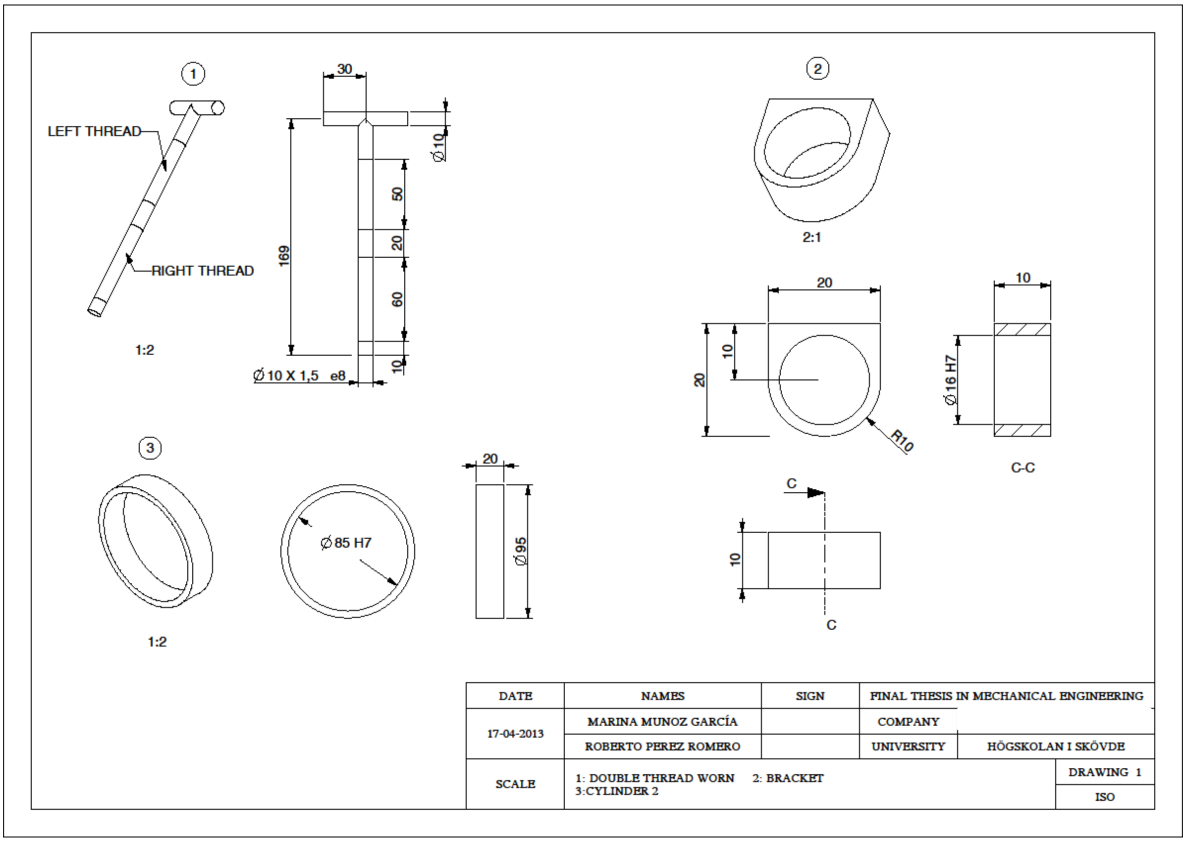
SUB-FUNCTION	SCORE
Group 1	
Develop a reliable operation	0.4
Have high safety	0.2
Have simple design	0.2
Do good operating	0.2
Group 2	
Control	0.6
Assemble different rings	0.2
Perform optimal fit	0.2

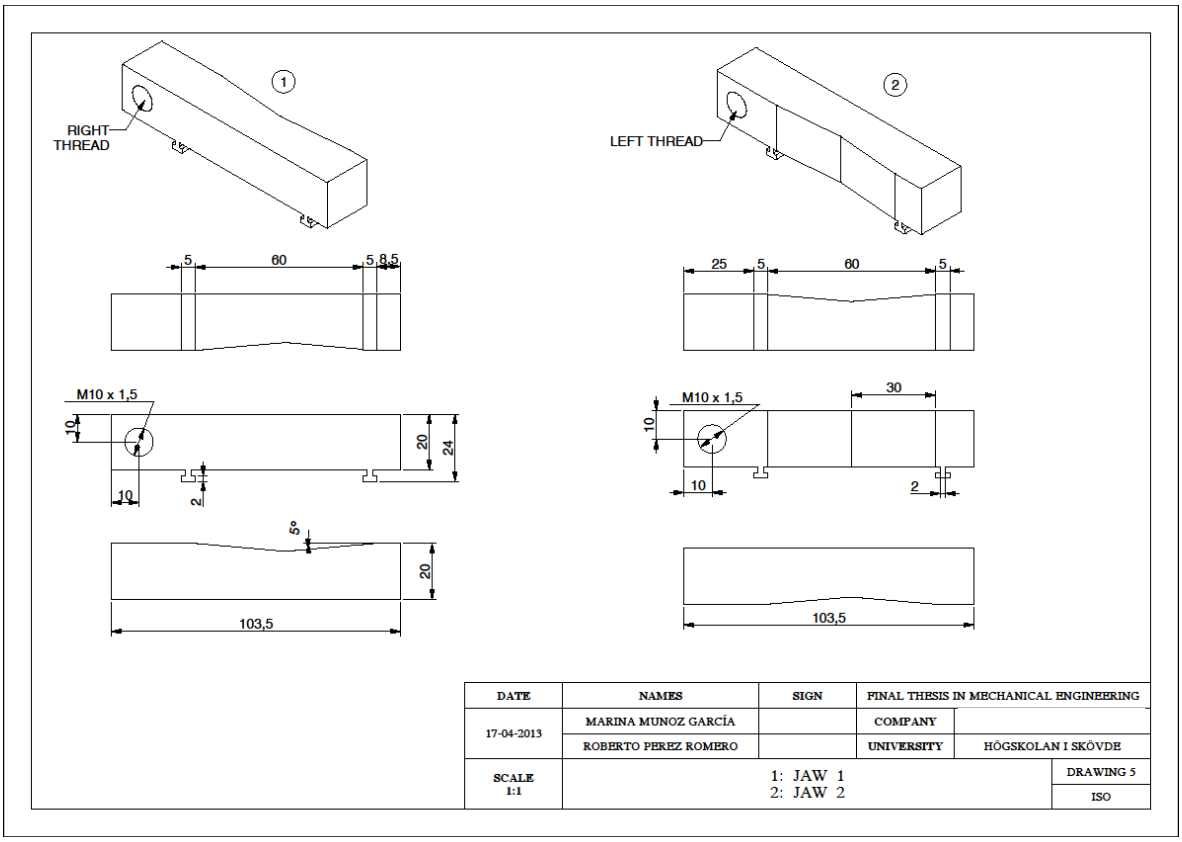
C. SUMMARY OF THE PRINCIPAL CHARACTERISTICS

Table 19: Summary of the main characteristics of each part from the test rig to assemble

MODEL	CHARACTERISTICS	
	Necessities	Qualities
	Perpendicular displacement without deviation in the stroke	Perpendicular displacement with an permitted error
	Controllable and measurable load and displacement	Load cell to measure the load and the displacement and an external control device to control the these parameters
	A load between 15 and 45 KN, with a permitted arror of 10N	Electronic control with a range between 0 – 50 kN
	Work space of 2m of stroke.	Boards movables and height customized
	Catalogue product and simple design	Catalogue product
	Capable of clamping shafts of 60 mm diameter	Range of 50-70 mm (customized)
	Strong Clamping without any clearance	Hydraulic clamping 2 kN
	Catalogue product or simple design	Catalogue product
	Clamping without any clearance	Mechanical safety
	Different sizes and shapes of rings	Flexible clamping
	Choose the orientation with a permitted error of 1º	Manual rotation with degrees scaled at the bottom
	Catalogue product	Simple design

D. DRAWINGS


LEFT THREAD
RIGHT THREAD
1:2
30
Ø10
50
20
60
10
169
Ø 10 X 1,5 e8
2:1
20
10
20
10
R10
Ø 16 H7
C-C
C
C
10
Ø 85 H7
20
Ø 95
1:2
DATE
NAMES
SIGN
FINAL THESIS IN MECHANICAL ENGINEERING
17-04-2013
MARINA MUNOZ GARCÍA
ROBERTO PEREZ ROMERO
COMPANY
UNIVERSITY
HÖGSKOLAN I SKÖVDE
SCALE
1: DOUBLE THREAD WORN 2: BRACKET
3:CYLINDER 2
DRAWING 1
ISO


RIGHT THREAD
LEFT THREAD
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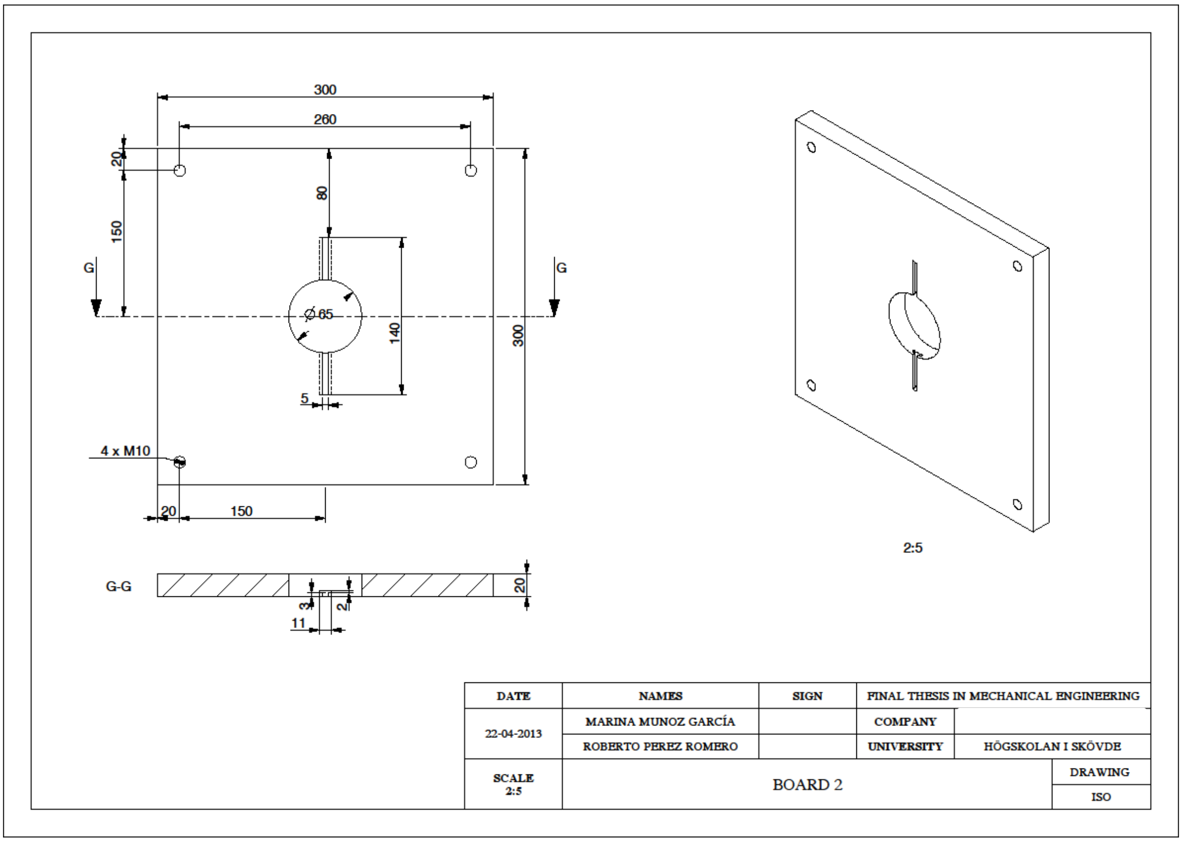
60
5 8,5
25
5
60
5
M10 x 1,5
10
20
24
10
2
M10 x 1,5
30
10
10
2
5°
20
103,5
103,5
DATE
NAMES
SIGN
FINAL THESIS IN MECHANICAL ENGINEERING
17-04-2013
MARINA MUNOZ GARCÍA
ROBERTO PEREZ ROMERO
COMPANY
UNIVERSITY
HÖGSKOLAN I SKÖVDE
SCALE
1:1
1: JAW 1
2: JAW 2
DRAWING 5
ISO


300
260
20
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150
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G
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140
300
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4 x M10
20
150
G-G
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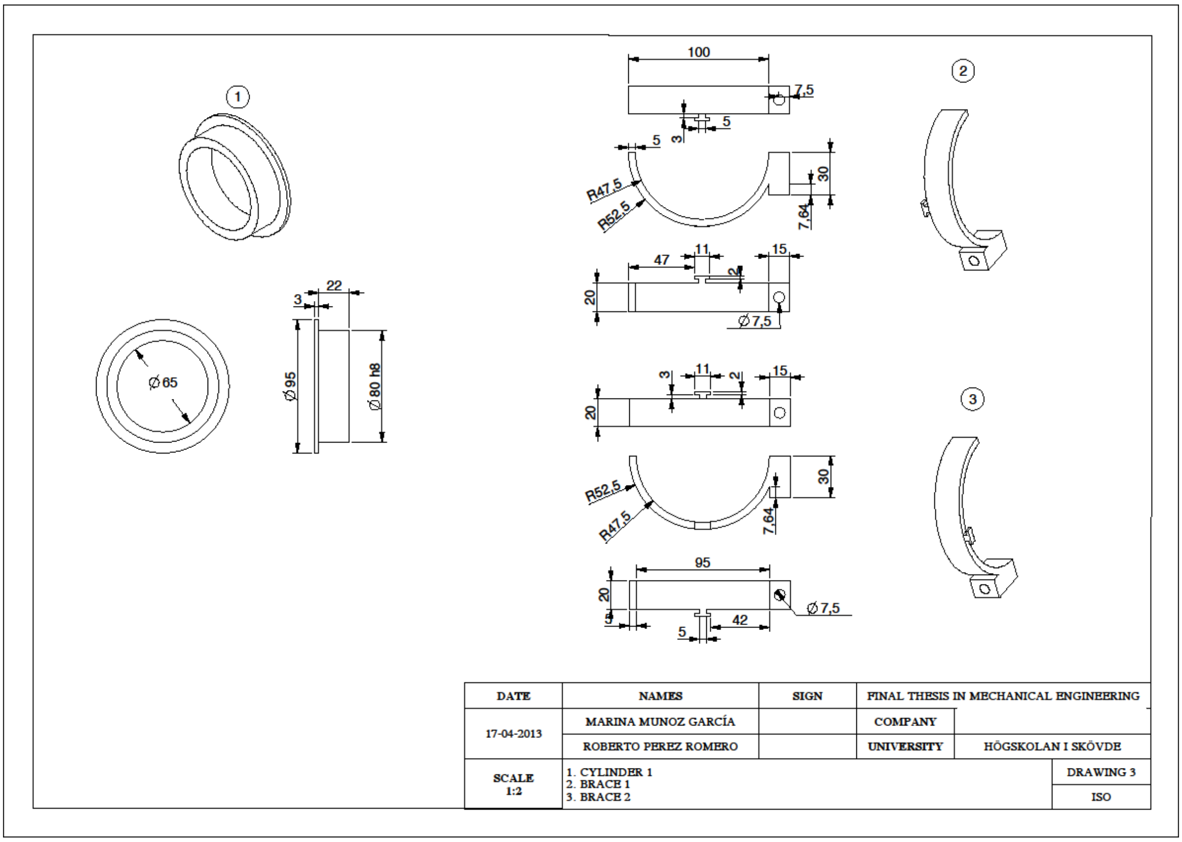
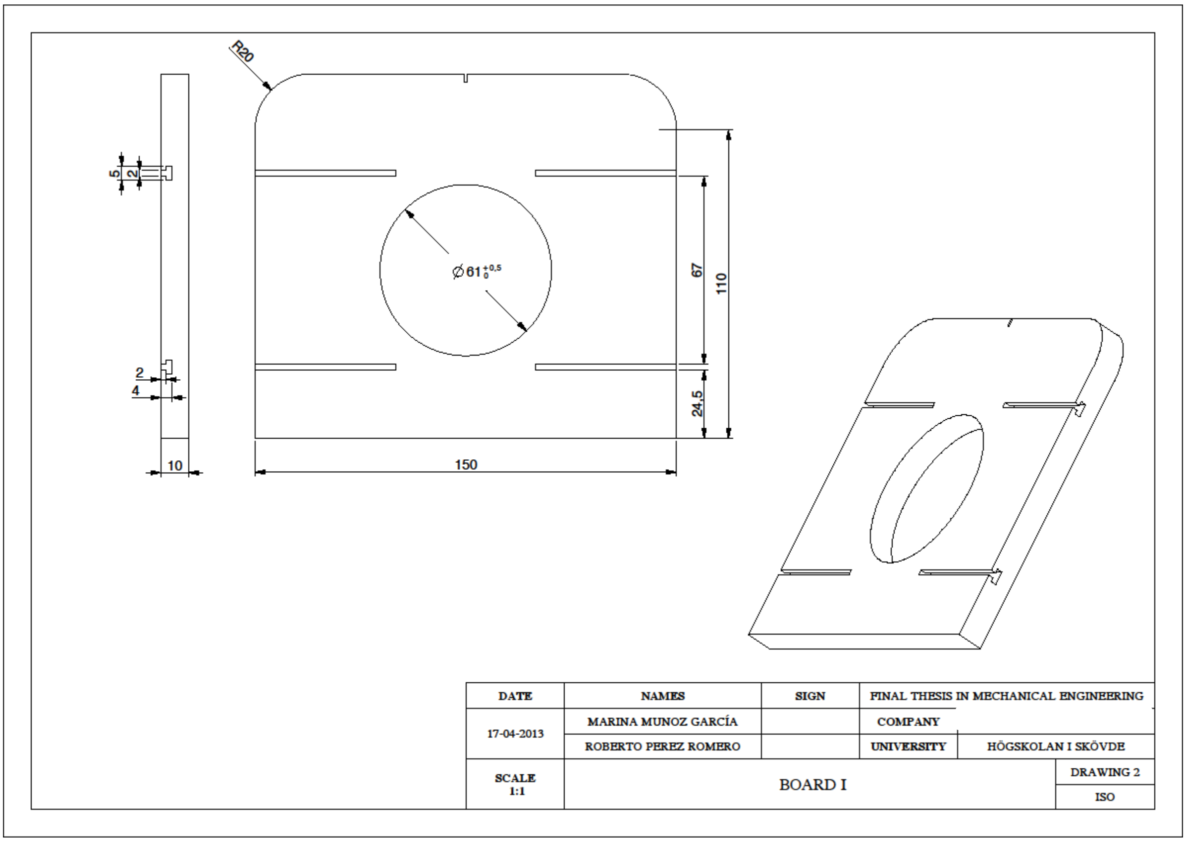
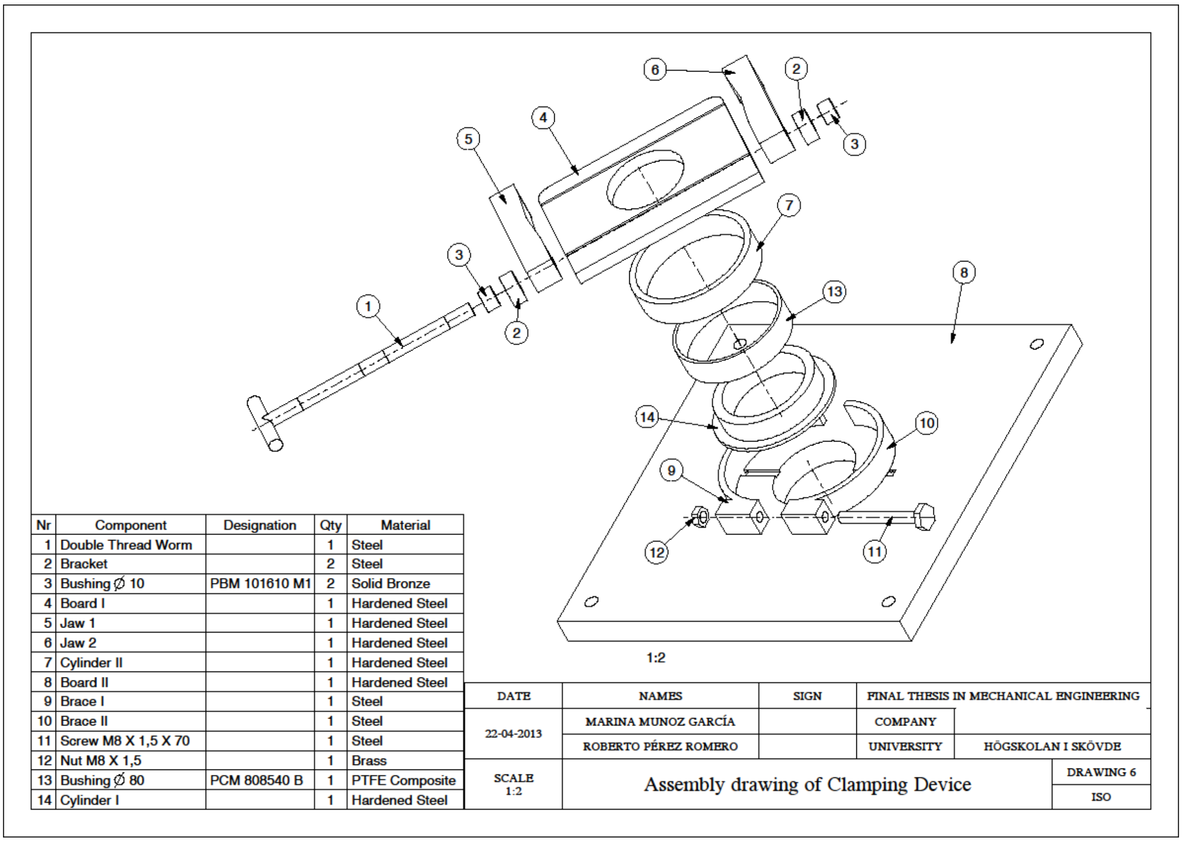
2
11
20
2:5
DATE
NAMES
SIGN
FINAL THESIS IN MECHANICAL ENGINEERING
22-04-2013
MARINA MUNOZ GARCÍA
COMPANY
ROBERTO PEREZ ROMERO
UNIVERSITY
HÖGSKOLAN I SKÖVDE
SCALE
2:5
BOARD 2
DRAWING
ISO


1
2
3
100
7,5
5
3
5
R47,5
R52,5
30
7,64
47
11
15
2
20
⌀7,5
22
3
⌀65
⌀95
⌀80 h8
3
11
2
15
20
R52,5
R47,5
30
7,64
95
20
⌀7,5
5
42
DATE
NAMES
SIGN
FINAL THESIS IN MECHANICAL ENGINEERING
17-04-2013
MARINA MUNOZ GARCÍA
COMPANY
ROBERTO PEREZ ROMERO
UNIVERSITY
HÖGSKOLAN I SKÖVDE
SCALE
1:2
1. CYLINDER 1
2. BRACE 1
3. BRACE 2
DRAWING 3
ISO





Nr	Component	Designation	Qty	Material
1	Double Thread Worm		1	Steel
2	Bracket		2	Steel
3	Bushing Ø 10	PBM 101610 M1	2	Solid Bronze
4	Board I		1	Hardened Steel
5	Jaw 1		1	Hardened Steel
6	Jaw 2		1	Hardened Steel
7	Cylinder II		1	Hardened Steel
8	Board II		1	Hardened Steel
9	Brace I		1	Steel
10	Brace II		1	Steel
11	Screw M8 X 1,5 X 70		1	Steel
12	Nut M8 X 1,5		1	Brass
13	Bushing Ø 80	PCM 808540 B	1	PTFE Composite
14	Cylinder I		1	Hardened Steel

E. MATERIAL PROPERTIES

HARDENING STEEL AISI 8620

AISI 8620 is a Nickel-Chrome-Moly Carburising Steel. It is mainly used in arbours, pinions, bushes, camshafts, kingpins, ratchets, gears, splines, shafts as well as high tensile and compressive applications un-carburised, but through hardened and tempered. Its principal properties are exposed in the following table (TATA Steel, 2013).

Table 17: Material properties of Hardening Steel AISI 8620

Physical Properties	
Density	7.83 g/cm^3
Thermal Properties	
Thermal conductivity (100ºC)	26 W/m-K
Processing Properties	
Melting Point	1427 ºC
Mechanical Properties	
Hardness HB	275
Yield Strength	690 MPa
Tensile Strength	925 MPa
Modulus of elasticity (tension)	193 GPa
Modulus of elasticity (torsion)	78 GPa
Chemical Analysis	
Carbon	0.20 %
Silicon	0.25 %
Manganese	0.80 %
Nickel	0.55 %
Chromium	0.5 %
Molybdenum	0.20 %

AISI-A2 TOOL STEEL

AISI-A2 is a cold work tool steel air or oil hardening. It is characterized by its good machinability, high stability after hardening, high compressive strength in addition to possess good wear resistance and hardenability (TATA Steel, 2013).

Table 18: Material properties of AISI-A2

Physical Properties	
Density	7.75 g/cm^3
Thermal Properties	
Thermal conductivity (100ºC)	26 W/m-K
Processing Properties	
Melting Point	1427 ºC
Mechanical Properties	
Hardness HB	215
Compressive Yield Strength Rc. 0.2	2.20 GPa
Modulus of elasticity (tension)	190 GPa
Modulus of elasticity (torsion)	78 GPa
Chemical Analysis	
Carbon	1.00 %
Silicon	0.30 %
Molybdenum	1.10 %
Vanadium	0.20 %
Chromium	5.30 %
Manganese	0.60 %

SOLID BRONZE

SKF Solid Bronze plain bearings are made of a multi-component bronze, whose designation is CuSn7ZnPb. Table 20 exposes the principal properties taken into account for a solid bronze plain bearing (SKF, 2013)

Table 19: Material properties of solid bronze

Permissible load (dyn/stat)	25/45 N/mm^2
Permissible sliding velocity	0.5 m/s
Friction coefficient (μ)	0.08 – 0.15
Temperature range	-40 – 250 °C

PTFE COMPOSITE

PTFE Composite is the material used in dry sliding plain bearings. It combines a principal steel layer to provide strength in addition to a PTFE-based self-lubricating sliding layer. Furthermore, an intermediate layer made of porous tin bronze improves the heat dissipation during its performance as well as assuring a strong bond between the external layers (SKF, 2013). Figure 58 shows a cross section on the PTFE Composite material.

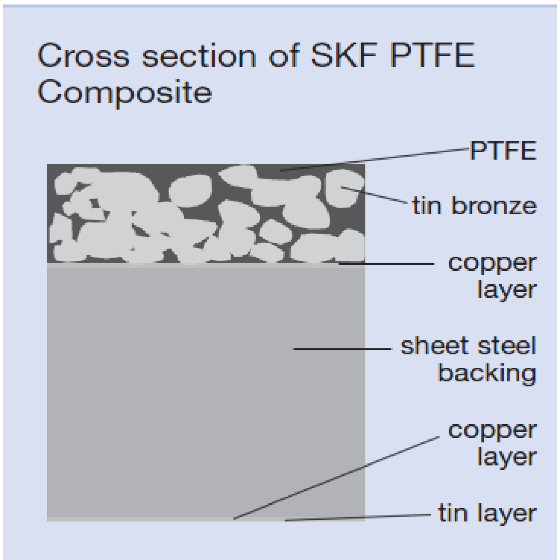


Figure 59: Cross section of SKF PTFE Composite (SKF, 2013)

Table 21 presents the principal characteristics to take into consideration to implement this material to manufacture bushings.

Table 20: Material properties of PTFE Composite

Permissible load (static/dynamic)	89/250 N/mm^2
Permissible sliding velocity	2.00 m/s
Friction coefficient (μ)	0.03 – 0.25
Temperature range	-200 – 250 °C

F.BUSHING CATALOG

SKF Solid Bronze

The all-round runner

The traditional and robust bushing material

No other cylindrical bushing is used in as many and as varied applications as solid bronze bushings. The solid bronze material is ideally suited for highly demanding applications in tough environments. SKF offers a standard assortment of both plain and flanged cylindrical bushings in accordance with ISO 4379 and DIN1850.

SKF Solid Bronze bushings offer many features and advantages such as:

- insensitive to dirty environment
- resistant to shock loads and vibrations at slow speeds
- enable operation with a poor shaft surface finish
- good resistance to corrosive conditions
- lubrication groove

Material

SKF Solid Bronze bushings are made of a multi-component bronze, CuSn7ZnPb, which has a very good sliding properties. All surfaces of the solid bronze bushings are machined.

Main applications[1)]

SKF Solid Bronze bushings are intended for oscillating movements in both rotational and axial directions. SKF Solid Bronze bushings are not intended for rotating movements at medium or high speeds.

Examples of applications are:

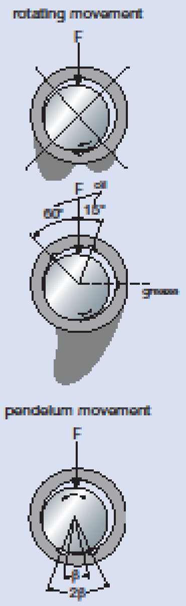
- construction machinery
- transport equipment
- pulp and papermaking machinery
- off-shore equipment

Lubrication

SKF Solid Bronze bushings are intended to be lubricated with oil or grease. Lubrication not only improves the sliding properties, but also reduces wear and prevents corrosion. Grease is usually used when lubrication is periodical, while in exceptional cases, an oil bath is used. Seals are recommended when the bushing is to be used in an aggressive environment.

All bushings with bore diameter of 14 mm and above incorporate an axial lubrication grove.

Positioning of lubrication groove at different running conditions



Characteristics:	
Permiss. load (dyn/stat), N/mm²	25/45
Permiss. sliding velocity, m/s	0,5
Friction coefficient μ (greased)	0,08 .. 0,15
Temperature range, °C	–40 .. +250
Application recommendations:	
Shaft tolerance	e7 – e8
Housing tolerance	H7
Shaft roughness R_a, μm	< 1,0
Shaft hardness, HB	> 165

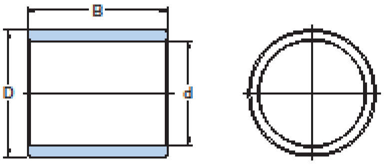
[1)] The performance of SKF Solid Bronze bushings depends on the interaction of load, lubrication, surface roughness, sliding velocity, and temperature encountered in specific applications.

SKF Solid Bronze – plain cylindrical bushings

Construction of designation:

PBM 20 28 20

- d = 20
- D = 28
- B = 20
- M: Metric
- B: Solid Bronze
- P: Plain bearing



Designation	d mm	D mm	B mm
PBM 051006 M1	5	10	6
PBM 051008 M1	5	10	8
PBM 051010 M1	5	10	10
PBM 061206 M1	6	12	6
PBM 061208 M1	6	12	8
PBM 061212 M1	6	12	12
PBM 071208 M1	7	12	8
PBM 071210 M1	7	12	10
PBM 071212 M1	7	12	12
PBM 081408 M1	8	14	8
PBM 081412 M1	8	14	12
PBM 081416 M1	8	14	16
PBM 091410 M1	9	14	10
PBM 091416 M1	9	14	16
PBM 091420 M1	9	14	20
PBM 101610 M1	10	16	10
PBM 101616 M1	10	16	16
PBM 101620 M1	10	16	20
PBM 121812 M1	12	18	12
PBM 121816 M1	12	18	16
PBM 121825 M1	12	18	25
PBM 142012 M1G1	14	20	12
PBM 142020 M1G1	14	20	20
PBM 142030 M1G1	14	20	30
PBM 152216 M1G1	15	22	16
PBM 152220 M1G1	15	22	20
PBM 152230 M1G1	15	22	30
PBM 162216 M1G1	16	22	16
PBM 162220 M1G1	16	22	20
PBM 162230 M1G1	16	22	30
PBM 172516 M1G1	17	25	16
PBM 172520 M1G1	17	25	20
PBM 172530 M1G1	17	25	30
PBM 182516 M1G1	18	25	16
PBM 182520 M1G1	18	25	20
PBM 182530 M1G1	18	25	30
PBM 202820 M1G1	20	28	20
PBM 202830 M1G1	20	28	30
PBM 202840 M1G1	20	28	40
PBM 223220 M1G1	22	32	20
PBM 223230 M1G1	22	32	30
PBM 223240 M1G1	22	32	40
PBM 253525 M1G1	25	35	25
PBM 253535 M1G1	25	35	35
PBM 253550 M1G1	25	35	50
PBM 284025 M1G1	28	40	25
PBM 284035 M1G1	28	40	35
PBM 284050 M1G1	28	40	50
PBM 304030 M1G1	30	40	30
PBM 304045 M1G1	30	40	45
PBM 304060 M1G1	30	40	60
PBM 354535 M1G1	35	45	35
PBM 354550 M1G1	35	45	50
PBM 354570 M1G1	35	45	70
PBM 405040 M1G1	40	50	40
PBM 405060 M1G1	40	50	60
PBM 405080 M1G1	40	50	80
PBM 455545 M1G1	45	55	45
PBM 455560 M1G1	45	55	60
PBM 455580 M1G1	45	55	80
PBM 506050 M1G1	50	60	50
PBM 506070 M1G1	50	60	70
PBM 5060100 M1G1	50	60	100
PBM 557050 M1G1	55	70	50
PBM 557070 M1G1	55	70	70
PBM 5570100 M1G1	55	70	100
PBM 607560 M1G1	60	75	60
PBM 607590 M1G1	60	75	90
PBM 6075120 M1G1	60	75	120
PBM 658060 M1G1	65	80	60
PBM 658090 M1G1	65	80	90
PBM 6580120 M1G1	65	80	120
PBM 708560 M1G1	70	85	60
PBM 708590 M1G1	70	85	90
PBM 7085120 M1G1	70	85	120
PBM 759070 M1G1	75	90	70
PBM 7590100 M1G1	75	90	100
PBM 7590140 M1G1	75	90	140

Other dimensions available on request

28

SKF PTFE Composite

The long runner

Long maintenance-free operating life due to low friction

In applications where other materials have shown insufficient operating life SKF PTFE Composite dry sliding bearings can be the solution. SKF PTFE Composite is specially designed to operate without lubricant and is particularly suited for high load/medium speed applications. SKF offers a full range of cylindrical bushings in accordance with ISO 3547 and DIN 1494 as well as flanged bushings, thrust washers and strip.

SKF PTFE Composite bearings offer many features and advantages such as:

- maintenance-free operation
- very good frictional properties
- high load capacity
- operating temperatures up to 250 °C
- sliding velocity up to 2 m/s
- small operating clearance

Material

SKF PTFE Composite dry sliding bearings combine the mechanical strength of steel with the low friction of a PTFE-based self-lubricating sliding layer. The intermediate layer of porous tin bronze guarantees a strong bond between the backing and sliding surface and also improves the dissipation of heat generated during operation. The bearing is available in two versions. One with a sliding layer without any lead. This version has the suffix E. Another version where the sliding layer contains a minor amount of lead incorporates the suffix B. To protect the bearings from corrosion the steel backing is tin-plated. All SKF PTFE Composite dry sliding bearings can be machined, except for the sliding surface. however, a calibration is possible within certain limits.

Main applications[1)]

SKF PTFE Composite dry sliding bearings are suitable for applications where the load and self-lubrication requirements are high.

Examples of applications are:

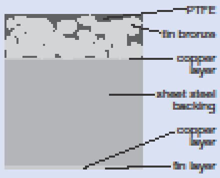
- automotive applications
- materials handling equipment
- home appliances and consumer goods
- textile machinery

Lubrication

The PTFE-based sliding surface permits smooth, low-friction operation without lubrication or maintenance. During the running-in phase part of the covering layer of SKF PTFE Composite dry sliding bearings is transferred to the mating surface and forms a physically bonded lubricant film.

The presence or continuous supply of oil or other non corrosive fluids may be advantageous and improve the perfomance of these bearings.

Cross section of SKF PTFE Composite



Characteristics:	
Permiss. load (dyn/stat), N/mm²	80/250
Permiss. sliding velocity, m/s	2,0 (p ≤ 1,0)
Friction coefficient μ	0,03 .. 0,25
Temperature range, °C	–200 .. +250
Application recommendations:	
Shaft tolerance	f7 – h8
Housing tolerance	H7
Shaft roughness R_a, μm	0 .. 0,4
Shaft hardness, HB	300 – 600

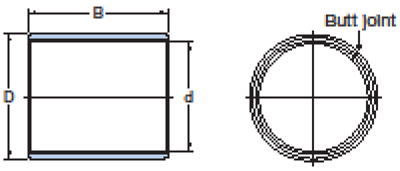
1) The performance of SKF PTFE Composite bearings depends on the interaction of load, lubrication, surface roughness, sliding velocity, and temperature encountered in specific applications.
Note: Because of the lead content, SKF PTFE Composite type B should not be used in contact with food, beverage or pharmaceutical products. Try to use SKF PTFE composite type E, SKF POM or Stainless Backed Composite bushings instead.

SKF PTFE Composite – plain cylindrical bushings

Construction of designation:

PCM 05 07 05 B

- PCM: Plain bearing, Composite, Metric
- 05: d
- 07: D
- 05: B
- B: sliding material, PTFE



Designation	d mm	D mm	B mm
PCM 455020 B	45	50	20
PCM 455020 E	45	50	20
PCM 455030 B	45	50	30
PCM 455030 E	45	50	30
PCM 455040 B	45	50	40
PCM 455040 E	45	50	40
PCM 455050 B	45	50	50
PCM 455050 E	45	50	50
PCM 505520 B	50	55	20
PCM 505520 E	50	55	20
PCM 505530 E	50	55	30
PCM 505530 B	50	55	30
PCM 505540 B	50	55	40
PCM 505540 E	50	55	40
PCM 505560 B	50	55	60
PCM 505560 E	50	55	60
PCM 556030 B	55	60	30
PCM 556030 E	55	60	30
PCM 556040 B	55	60	40
PCM 556040 E	55	60	40
PCM 556060 B	55	60	60
PCM 556060 E	55	60	60
PCM 606520 B	60	65	20
PCM 606520 E	60	65	20
PCM 606530 B	60	65	30
PCM 606530 E	60	65	30
PCM 606540 B	60	65	40
PCM 606540 E	60	65	40
PCM 606560 B	60	65	60
PCM 606560 E	60	65	60
PCM 606570 B	60	65	70
PCM 606570 E	60	65	70
PCM 657030 B	65	70	30
PCM 657030 E	65	70	30
PCM 657050 B	65	70	50
PCM 657050 E	65	70	50
PCM 657070 B	65	70	70
PCM 657070 E	65	70	70
PCM 707540 B	70	75	40
PCM 707540 E	70	75	40
PCM 707550 B	70	75	50
PCM 707550 E	70	75	50
PCM 707570 B	70	75	70
PCM 707570 E	70	75	70

Designation	d mm	D mm	B mm
PCM 758060 B	75	80	60
PCM 758060 E	75	80	60
PCM 758080 B	75	80	80
PCM 758080 E	75	80	80
PCM 808540 B	80	85	40
PCM 808540 E	80	85	40
PCM 808560 B	80	85	60
PCM 808560 E	80	85	60
PCM 8085100 B	80	85	100
PCM 8085100 E	80	85	100
PCM 859030 B	85	90	30
PCM 859030 E	85	90	30
PCM 859060 B	85	90	60
PCM 859060 E	85	90	60
PCM 909560 B	90	95	60
PCM 909560 E	90	95	60
PCM 9095100 B	90	95	100
PCM 9095100 E	90	95	100
PCM 9510060 B	95	100	60
PCM 9510060 E	95	100	60
PCM 95100100 B	95	100	100
PCM 95100100 E	95	100	100
PCM 10010560 B	100	105	60
PCM 100105115 B	100	105	115
PCM 11011560 B	110	115	60
PCM 110115115 B	110	115	115
PCM 12012560 B	120	125	60
PCM 120125100 B	120	125	100
PCM 130135100 B	130	135	100
PCM 14014560 B	140	145	60
PCM 140145100 B	140	145	100
PCM 15015560 B	150	155	60
PCM 15015580 B	150	155	80
PCM 150155100 B	150	155	100
PCM 160165100 B	160	165	100
PCM 180185100 B	180	185	100
PCM 200205100 B	200	205	100

40