



Kitchen robot prod. line development. Proj. of Bowden cables cutting and thermal forming machine.

JAKUB RADWANSKI

Janeiro de 2016

ERASMUS PROJECT

**Kitchen robot production line development.
Project of Bowden cables cutting and thermal forming machine.**

Author

Jakub Radwański (1150496)

Acknowledgements

At the beginning of this work, I would like to express my gratitude for Professor Francisco J. G. Silva. Without his efforts I would not even think about work in any Portuguese industrial company and probably spend this semester trying not to die of boredom during some classes, listening to teachers speaking language that I do not understand at all. In *PR* I had a great chance to gather a lot of new experience, improve my skills as mechanical engineer and meet wonderful people.

I want to say thank you to Engineers Vasco and Mario – my managers in *PR*. Thanks for your time, advices, patience and sharing wisdom and knowledge.

In the end I also must mention about Antonio, Joel, Diogo, Stefan and all the rest of you, guys. It was a wonderful time, we shared meals and free time, moments of laugh, hard work and difficulties as well. You accepted me as a member of your crew and made my time in *PR* a pleasure. Thank you for all!

Abstract

This document presents particular description of work done during student's internship in *PR Metal* company realized as ERASMUS PROJECT at ISEP. All information including company's description and its structure, overview of the problems and analyzed cases, all stages of projects from concept to conclusion can be found here.

Description of work done during the internship is divided here into two pieces. First part concerns one activities of the company which is robotic chefs (kitchen robot) production line. Work, that was done for development of this line involved several tasks, among them: creating a single-worker montage station for screwing robots housing's parts, improve security system for laser welding chamber, what particularly consists in designing automatically closing door system with special surface, that protects against destructive action of laser beam, test station for examination of durability of heating connectors, solving problem with rotors vibrations. Second part tells about main task, realized in second half of internship and stands a complete description of machine development and design. The machine is a part of car handle latch cable production line and its tasks are: cutting cable to required length and hot-forming plastic cover for further assembly needs.

Keywords

Production line, kitchen robot, assembly line, montage station, test station, laser welding, security Car handle latch cable, cutting machine, pneumatic press, machining.

List of Contents

Acknowledgements.....	3
Abstract	4
List of Contents	5
List of Tables.....	8
List of Figures	9
List of Symbols and Abbreviations	11
1. Introduction.....	13
1.1 Company characterization	13
1.2 The Problem.....	13
1.3 Strategy	14
1.4 Methods.....	15
PART I.....	17
2. Protection of laser chamber.....	18
2.1 Case introduction.....	18
2.1.1 Description of laser unit	18
2.1.2 Previous protection system.....	19
2.1.3 Comparison of laser beam protection methods	20
2.1.4 Choosing methods.....	21
2.2 Automatic system of hermetic doors	21
2.2.1 Sketch of solution proposals	22
2.2.2 Kinematic system synthesis.....	23
2.2.3 Cylinder and linear system selection.....	24
2.2.4 Construction solutions overview.....	26
2.2.5 Strength analysis	27
Fig 2.12 Render image of whole 3D model of automatic doors.	28
2.2.6 Pneumatic system for cylinder control and sensors for process control.....	28
2.3 Summary	29
3. Balancing rotor of the machine.....	30
3.1 Case characteristics.....	30
3.1.1 Rotor as a part of electric power motor.....	30
3.1.2 Description of case	30
3.2 Solution	31
3.2.1 Inputs and measured values interpretation.....	31

3.2.2 Method of balancing	32
3.2.3 Searching precise milling parameters	34
3.3 Manual for operator	35
3.4 Simulation	37
3.5 Summary	38
4. Milling machine improvement	39
4.1 Primary concept	39
4.2 Final concept	40
5. Test station for electromechanical connection.....	43
5.1 Heating connector and its test.....	43
5.2 Station overview	43
5.3 Pneumo-electronic system for controlling testing process	44
5.4 Gluing connectors to cups	45
5.5 Summary	46
6. Screwing station	48
6.1 Issue description	48
6.1.1 Assembly line.....	49
6.2 Solution proposals	50
6.2.1 Partially automatic system	50
6.2.2 Fully automatic system.....	50
6.2.3 Single operator station.....	50
6.3 Manually operating station.....	51
6.3.1 Description of forms for housings	51
6.3.2 Algorithm of work	53
6.3.3 Summary	54
Part II.....	56
7. Background.....	57
7.1 Mechanical cables.....	57
7.2 Cutting methods and machines.....	58
7.3 Blades and knives.....	60
7.3.1 Materials	61
7.4 Thermal forming of small size structures	63
7.5 Summary	63
8. Development.....	65
8.1 Problem analysis.....	65

8.2 Brainstorming, preliminary drafts, selection of solution.....	65
8.3 Final solutions development and detailed description	67
8.3.1 Machine overview	67
8.3.2 Processes description.....	68
8.3.3 Cylinder for cutting system	69
8.3.4 Press guidelines.....	69
8.3.5 Blades	70
8.3.6 Heating, temperature measuring, isolation.....	70
8.3.7 Conduit holding system.....	71
8.3.8 Clamps and springs system	72
8.3.9 Frame construction	74
8.3.10 Protection.....	74
8.3.11 Smart systems	75
8.4 Budgeting	77
8.5 Critical analysis and prospects of improvement.....	78
8.6 Maintenance guidelines.....	79
8.6.1 Documentation	79
8.6.2 Manufacturing and assembling.....	80
8.6.3 During normal work	80
9. Concluding remarks.....	81
10. Bibliography and others sources of information	82
10.1 Books and scientific papers	82
10.2 Internet sources.....	83
Appendix	85

List of Tables

Table 1.1 Tasks and realization time list.	15
Table 2.1 Parameters of Rofin FL-020 laser unit [I].	18
Table 2.2 I_p as function of z_f	19
Table 2.3 Parameters of structure taken for simulation.	24
Table 2.4 Table of sensor binary states and information that they bring.	29
Table 3.1 Values of sine and cosine function.	35
Table 3.2 Table of conversion "tan" to "a" values.	36
Table 3.3 Table of signs meaning.	36
Table 3.4 Table of converting "e" to "b" values.	36
Table 3.5 Table of milling parameters calculations.	37
Table 3.6 Values of center of mass position, product moments of inertia and forces in bearings before and after milling (11000 rpm).	38
Table 5.1 Parts list for pneumatic system of test station.	45
Table 6.1 Comparing advantages and disadvantages of stations.	51
Table 8.1 Springs parameters.	73
Table 8.2 Cost of material and manufacturing.	77
Table 8.3 Cost of purchased parts.	77
Table 8.4 SWOT chart for project.	79

List of Figures

Fig 1.1 <i>PR Grupo</i> and companies that belong to the corporation.	13
Fig 1.2 Strategy and workflow around the project.	14
Fig 1.3 GANTT chart for tasks realization (blue – group of tasks time realization, red – relevant task, green – partially relevant tasks.	16
Fig 2.1 Depth of welding as function of surface power intensity for steel S235 [II].	19
Fig 2.2 Actual view of welding station.	20
Fig 2.3 Geometrical condition for welding station (dimensions in millimeters).	21
Fig 2.4 Ideas around kinematic system of doors mechanism.	22
Fig 2.5 a) kinematic structure and some main dimensions; b) explanation of movement: red color – 1 st position, blue color – 2 nd position, brown arrows – directions of parts displacements.	23
Fig 2.6 Basic 3D model for simulation needs.	24
Fig 2.7 Plot presenting cylinder force (blue curve) and velocity (green curve) during single cycle of work.	25
Fig 2.8 Pictures of DSNU-50-150-P and HG-15C.	25
Fig 2.9 Curves presenting values of forces in kinematic joints.	26
Fig 2.10 Some construction solutions applied in project (part. I).	26
Fig 2.11 Some construction solutions applied in project (part. II).	27
Fig 2.12 Render image of whole 3D model of automatic doors.	28
Fig 2.13 a) pneumatic installation of cylinder, b) sensors location, c) <i>IQ08-04NPOKW2S</i> 29	29
Fig 3.1 a) Model of a rotor; b) picture of real part.	30
Fig 3.2 <i>ND B012 Digital balancing machine</i> : balancing machine a) front panel; b) mechanical equipment.	31
Fig 3.3 a) Dynamic reactions in bearings: a) curves describing amplitudes, b) view of vectors of reactions on rotor.	32
Fig 3.4 Geometrical properties of the rotor and values used during milling.	34
Fig 3.5 View of rotor simulation model: a) before milling, b) after milling.	37
Fig 4.1 a) View of standard milling machine b) damaged rotor after milling process.	39
Fig 4.2 Primary concept of machine improvement.	40
Fig 4.3 Detail view of rotor fixing.	40
Fig 4.4 Detail view of rotor fixing.	41
Fig 4.5. Shaft support mathematical model [XIV].	41
Fig 4.6 View of improved machine table.	42
Fig 5.1 Heating connector 43	43
Fig 5.2 a) Pneumatic cylinder, <i>DFM-12-25-P-A-GF</i> ; b) <i>Sauterelle 70^a</i> , toggle clamps.	43
Fig 5.3 Heating connector test station: a) render of 3D model; b) view of the real station.	44
Fig 5.4 Pneumatic system for test station.	45
Fig 5.5 Primary version of gluing station: a) single cup view, b) view of the whole station.	46
Fig 5.6 Final version of gluing station.	47
Fig 6.1 Both parts of robot housing.	48
Fig 6.2 Assembly line sketch.	49
Fig 6.3 View of a single station in the assembly line.	49
Fig 6.4 a) Structure of typical 3-DOF gantry manipulator [XIX], b) structure of typical 3-DOF SCARA manipulator [XX].	50
Fig 6.5 a) View of conceptual model of screwing station, b) bottom view of the holes in bottom form.	51
Fig 6.6 Section view of bottom form and screw driver.	52

Fig 6.7 Screwing station after upgrade.	52
Fig 6.8 Algorithm of work at the station.	54
Fig 7.1 Exploded view of Bowden cable [XXI].	57
Fig 7.2 Conduit of Bowden cable by SCS: a) section view, b) picture of real part	57
Fig 7.3 a) water jet [21], b) laser cutting [22], c) ultrasonic waterjet [24].	58
Fig 7.4 a) cable cutting and measuring machine in accordance with [25], b) hand-held device for cutting and stripping cables [26], c) cable cutting and stripping machine [27].	59
Fig 7.5 Round blades: a) external shape, b) geometry of blades [XXIV].	60
Fig 7.6 Different shapes of cutting blades [28].	61
Fig 7.7 a) Band saw blades [XXVI]; b) rectangular blades for metal sheets and plates cutting [XXVII].	61
Fig 7.9 Methods of temperature plastics forming: a) hot embossing [XXXI], b) hot wire cutter [XXXII].	Błąd! Nie zdefiniowano zakładki.
Fig 7.8 Table containing minimum requirements that steel must met to be classified as HSS (according to ASTM) [31].	62
Fig 8.1 Conceptual sketch of the machine (1).	65
Fig 8.2 Conceptual sketch of the machine (2).	66
Fig 8.3 Conceptual sketch of the machine (3).	66
Fig 8.4 Machine overview.	67
Fig 8.5 Thermoforming and cutting process shown in steps.	68
Fig 8.6 Direction of cutting forces.	69
Fig 8.7 a) Linear sliding bushings , b) Linear guidelines (columns) by <i>Coferac</i> [XXXIII].	70
Fig 8.8 a) Blade montage, b) Linear guidelines by <i>Coferac</i> [XXXIII].	70
Fig 8.9 Heating, temperature measuring and isolation system in press table.	71
Fig 8.10 a) cartridge heaters b) thermocouples [XXXVI] c) celeron [XXXV].	71
Fig 8.11 Conduit immobilizing and grooves making system.	72
Fig 8.12 Section view of clamps and springs system.	72
Fig 8.13 Render image: clamps and springs system.	73
Fig 8.14 Frame construction: a) exploded view, b) assembly view, c) bottom connection, d) top connection.	74
Fig 8.15 Frame construction: a) exploded view, b) assembly view, c) bottom connection, d) top connection.	75
Fig 8.16. Dismounting all the tooling.	76
Fig 8.17. Dismounting bottom blade.	76
Fig 8.18. Dismounting top blade.	76
Fig 8.19 Estimated cost of mechanical equipment of machine.	78

List of Symbols and Abbreviations

A	Surface area (square meters – m^2)
ANSI	The American National Standards Institute
ASTM	The American Society for Testing and Materials
BPP	Beam Parameter Product (of laser beam)
CNC	Computer Numerical Controls
CDRH	Center of Devices and Radiological Health
d	Shaft diameter (measured in millimeters)
D	Hole diameter (measured in millimeters)
DOF	Degrees of freedom
g	Gravitational acceleration ($9,81 m/s^2$)
i_{min}	Smallest radius of gyration (measured in millimeters)
I_x	Mass moment of inertia (axial)
I_p	Surface power intensity (Watts per square centimeter – W/cm^2)
IEC	International Electrotechnical Commission
k_l	Number of links in kinematic system
M_r	Real mobility of kinematic system
M_x	Momentum working on body at x-axis
m	Mass of an object (measured in grams or kilograms)
MDF	Medium density fiberboard (name of material)
MPa	Magapascal (unit of pressure)
Nr.	Number (acronym)
OD	Optical Density (no unit)
P	Power (nominally measured in Watts – W)
p_i	Number of kinematic pairs, i-class
PE	Polyethylene
PLC	Programmable Logic Controller
PP	Polypropylene
r	Arm of force (measured in millimeters or meters)
R_h	Border tension value (for Hook's law application)
r_f	Radius of laser beam in the focus (measured in millimeters or meters)
R_p	Proportionality limit of material (measured in MagaPascal)
rad	Radian (unit of angle)
rpm	Rotations per minute (unit of angular velocity)
SWOT	Strengths, Weaknesses, Opportunities, Threats
t	Time (measure in seconds)
v	Velocity, (measure in meters per seconds)
z_s	Safety coefficient (no unit)
z_f	Distance from focus of a beam (measured in millimeters)
Δr_g	Distance between center of gravity and an axis of rotation of an object (measured in millimeters)
λ	Wavelength (nominally in nm – nanometers) or slenderness of a rod (no unit)
θ	Propagation angle (of laser beam, measured in radians)

μm	<i>Micrometer (0,001 of millimeter)</i>
ρ	<i>Density of material (measured in kilograms per cubic meter)</i>
ω	<i>Angular velocity (measured in radians per second)</i>

1. Introduction

Following report is one of final results of 30 ECTS ERASMUS PROJECT carried out in academic year of 2015/2016, winter semester, performed during practice in *PR Metal*. Internship was divided into a few parts, among which a development of kitchen robots production line and complete project of cutting press for commercial needs were carried out.

1.1 Company characterization

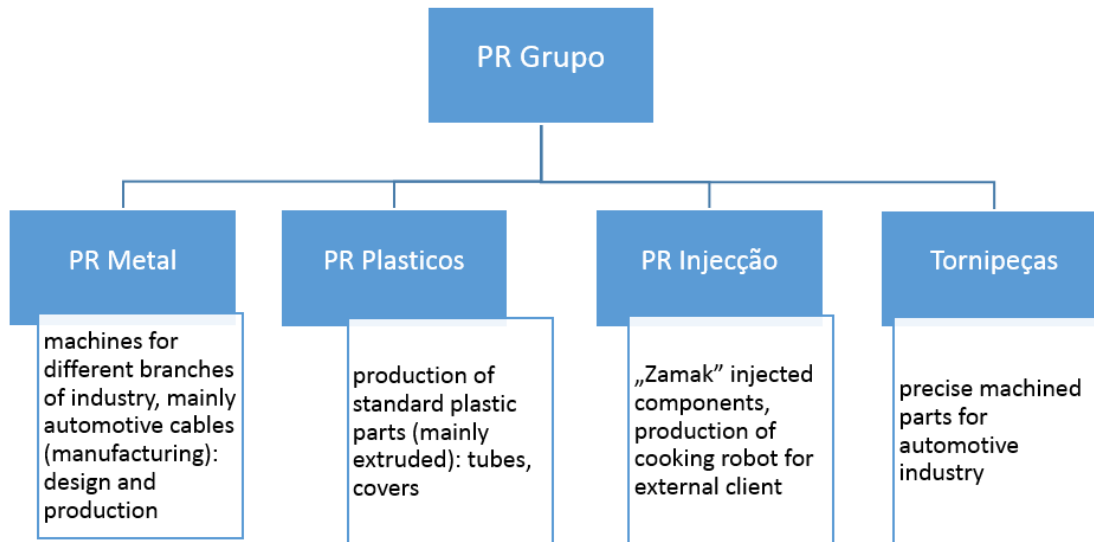


Fig 1.1 *PR Grupo* and companies that belong to the corporation.

PR Grupo is a corporation containing four industrial units (Fig 1.1 contains profiles of each sub company) which are generally engaged in production of industrial components. All the units have their building in small industrial zone in Maia, Oporto. About one hundred and twenty employees work in all units together. There are three chairmen on in the management of the company. Each unit has their managers which are responsible for work coordination, human resources, dealing with customers, purchases, etc. Main group of employees are manual workers which have their coordinators, reporting to managers. There is a group of engineers (production engineers, designers, drafters) which cooperate with manual workers. My internship took place in two of business units: *PR Metal* and *PR Injecção*.

1.2 The Problem

At the beginning of the project there was a series of tasks related to problems appearing in production line of kitchen robot which was made in *Injecção* unit. All those tasks were very different and varied, requiring several fields of engineering skills and knowledge: from basic physics and mathematics (in case of solving problem with balancing the rotors of robot), through assurance of safety work (during developing automatic system of door to close laser chamber) to modelling and technical documentation making (e. g. when milling machine equipment was improved). All problems will be described in introductions to subchapters.

Main part of the whole internship was dedicated to a complete design of cutting machine. The commercial machine was made to order of Germany's company: *SCS*. Cutting press is one link in the chain of whole manufacturing process, which final product is Bowden cable for car doors application. The press must do two tasks: main is cutting cable into required length, and

secondary is making specific grooves using two hot pairs of rib patterns and forcing them to contact with plastic cover. Aforementioned grooves are required for connection a cable with end inserted parts. Processes that precede cutting are: assembling components of latch cable, hot extrusion, cooling and pulling.

1.3 Strategy

The strategy taken for the project described in is suitable for single person who works in periodical consultation with superior. In that case the role of superior contains such activities as: discussing main parts of the project, transferring information from client (in case of external character of project) and questions about client's needs and consulting with experts inside the company (due to language barrier). The work of student bases on creating ideas on each level of development of the project beginning with concept, through 3D modelling, selecting purchasing items, etc. until final technical documentation and whole description is done. Student was consulting only relevant cases of the project that were particularly important, taking into account company's manufacturing possibilities, client needs, expenses. In case of engineering calculations, materials selection, etc. research in adequate literature was done. Also requests to purchasing parts suppliers belonged to student duties; information about technical documentation and 2D manufacturing drawings rules, mandatory in our company, were consulted with office engineers. Student also prepared promotional tools about the product, that were later translated by other employees for presentation needs. Each stage of work contained two brain storms with superior. First was just after presenting basic ideas to select the main current, second before finishing the particular stage, to correct very small details. All information about workflow around the project, described above are shown Fig 7.2.

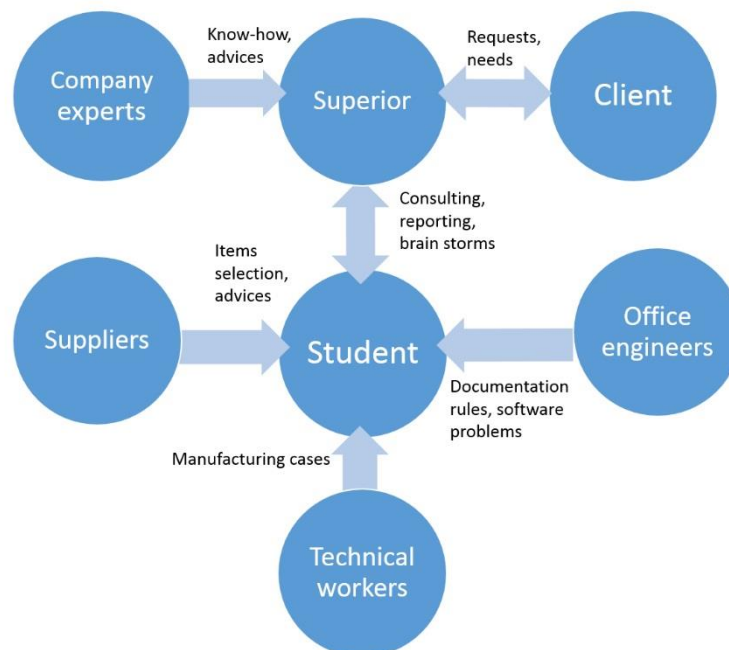


Fig 1.2 Strategy and workflow around the project.

1.4 Methods

First part of project was needed to be done in request-work-done mode, which means that tasks were given one after another and time realization was not precise. For this reason scheduling and phases planning did not have place. In second part of the project were divided into many phases. A list of tasks with beginning time and amount of days they took is included in Table 1.1. On its base the GANTT chart was created (Fig 1.2).

Table 1.1 Tasks and realization time list.

Task	Start Date	#Days Required
Getting familiar with company, units, equipment, products and methods	2015-10-05	30
Gathering knowledge about production line	2015-10-05	8
Production line development	2015-10-07	50
Protection of laser chamber	2015-10-07	20
Balancing rotor of the machine	2015-11-02	3
Test station for electromechanical connection	2015-11-06	3
Gluing connectors to cups	2015-11-09	2
Screwing station	2015-11-11	14
Inventor training/drawing from 3D models	2015-11-25	5
Milling machine development	2015-11-26	5
Machine for conduit cutting and temperature forming	2015-12-01	60
Brainstorming, ideas, concept	2015-12-01	3
Creating basic 3D model	2015-12-02	5
1st results presentation	2015-12-10	1
Developing 3D model	2015-12-08	33
Searching for purchasing parts	2015-12-20	15
Engineering calculations	2015-12-09	20
2D documentation	2016-01-10	3
2nd final results presentation	2016-01-13	1
2nd results presentation	2016-01-13	1
Corrects and patches	2016-01-14	7
Final results presentation	2016-01-21	1
Assembly manuals for workers	2016-01-25	2
Promotional tools for client	2016-01-27	2
Report and presentation	2015-12-01	60

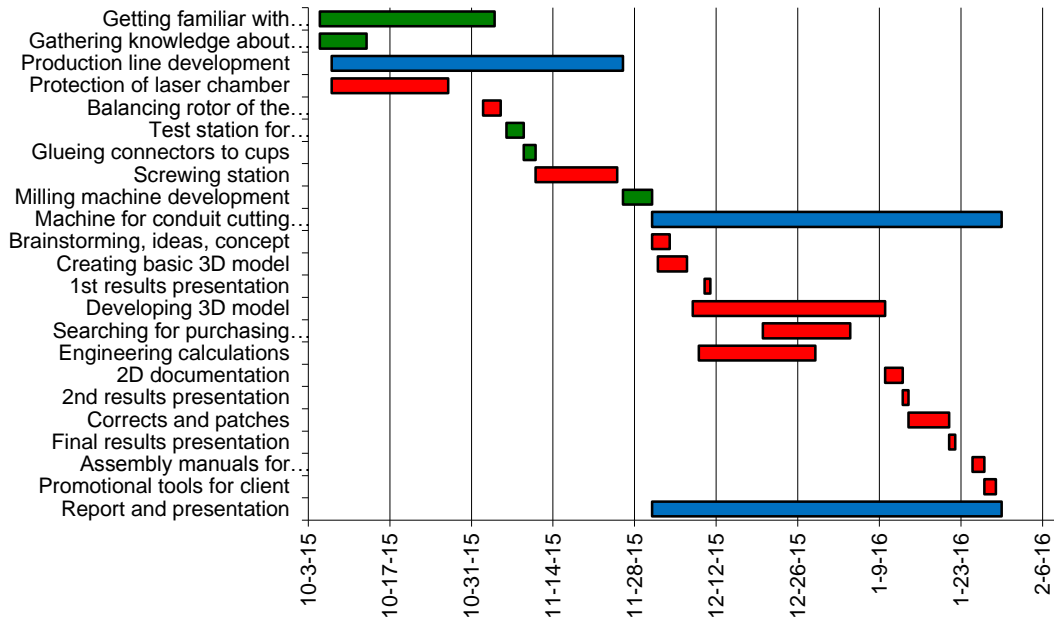


Fig 1.3 GANTT chart for tasks realization (blue – group of tasks time realization, red – relevant task, green – partially relevant tasks).

Part I:

Kitchen robot production line development

2. Protection of laser chamber

First of the tasks made during the internship in *PR* was improving previous coarse secure system. This chapter tells about all steps of this work from analyzing laser parameters, through choosing the way of protection and development of selected idea.

2.1 Case introduction

The robot has a special cup, in which the whole cooking process is made. The cup contains a couple of parts, including heating system. Some plates are welded to the main part of cup, where continuous laser is used to this work. The laser has very high power intensity, which allows steel to melt or being welded even in far fields, it might be very dangerous for humans eyes and rest of the body as well.

2.1.1 Description of laser unit

Laser unit, a part of welding station is a product of *Rofin* company, model FL-015. Every important parameter of laser is listed in Table 2.1 [I].

Table 2.1 Parameters of Rofin FL-020 laser unit [I].

Laser parameter	value
Power:	1,5 kW
Type of laser unit:	CO ₂
Wavelength:	10,6 μm
BPP:	1,5*10 ⁻⁹ m*rad
Radius of beam in the focus:	0,05...1,00 mm (adjustable)
Angle propagation of laser beam:	30,0...1,5*10 ⁻⁶ rad (dependent of radius value)

Laser beam after passing the focus becomes cone-shaped. Angle propagation of laser beam is the opening angle of this cone (measured in radians). Focus is the location, where the beam has the smallest cross-sectional, circular area. The BPP parameter is a constant value, characteristic for each laser unit [II]. Solving the equation (2.1) it is easy to find θ for known r_f .

$$BPP = \theta * r_f \quad (2.1)$$

One of the most significant variables, deciding about possible applications of laser unit power intensity. It is defined as shown in (2.2) equation.

$$I_p = \frac{P}{A} \quad (2.2)$$

However, surface area of beam section increases with the distance from focus of the beam (see equation (2.3)).

$$A = \pi * r^2 = \pi * [z_f * \tan(\theta)]^2 = \pi * [z_f * \tan(\theta)]^2 = \pi * \tan^2(\theta) * z_f^2 \quad (2.3)$$

in distance z_f [cm²] can be easily calculated for FL-020 using the (2.4) equation. To show the lowest possible intensity as distance function, highest value of θ was taken.

$$I_p = \frac{P}{A} = \frac{P}{\pi * \tan^2(\theta) * z_f^2} = \frac{1,5 * 10^3}{\pi * \tan^2(30,0 * 10^{-6}) * z_f^2} = \frac{1}{z_f^2} * 5,3 * 10^{11} \quad (2.4)$$

If z_f is measured in centimeters, than I_p unit is W/cm^2 . Example values of I_p as function of z_f were presented in Table 2.2 (values in the table calculated with use of equation (2.2)).

Table 2.2 I_p as function of z_f .

z_f [cm]	I_p [W/cm^2]
1	$5,3 * 10^{11}$
10	$5,3 * 10^9$
100	$5,3 * 10^7$
1000	$5,3 * 10^5$

To understand how high values these are, a plot shown on Fig 2.1 was enclosed. It is easy to realize that if laser beam will not find any barrier on its way, it can easily weld a few millimeters steel even from a couple of meter distance. It brings really big risk for machine operators working without proper protection.

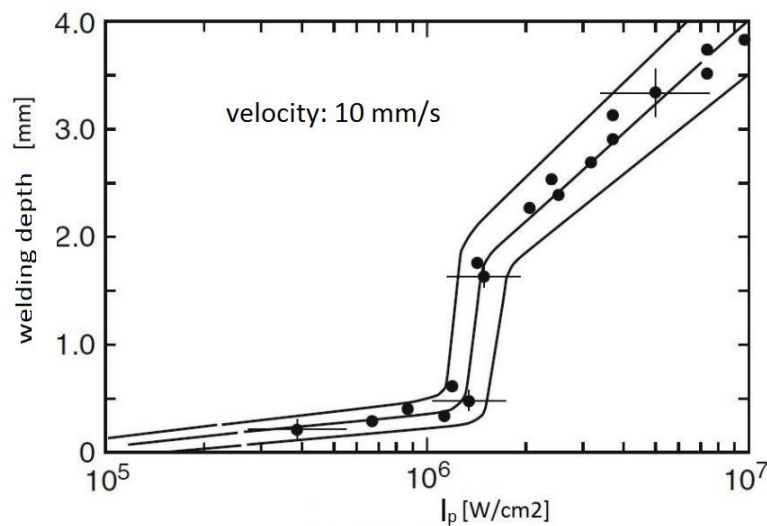


Fig 2.1 Depth of welding as function of surface power intensity for steel S235 [II].

2.1.2 Previous protection system

The Fig 2.2 presents current view of welding station. Laser unit, generates beam, transported by optical fiber to the head (1), fixed on manipulator (2), which is closed in welding chamber (3). Access to this chamber is possible by door (4), side walls of the chamber have entrances which allow the movable table (5) to get welded parts between the chamber and preparing stations (6, 7) where parts are fixed to the base. When table reaches a position required for welding, the plates (8 – only one visible on the picture) close entrances to welding chamber. However, this closing system is not hermetic, leaves wide gaps. To make operating safer, a contactor was installed (9). Since doors are open the PLC controller unable to start or continue welding due to information taken from this sensor.

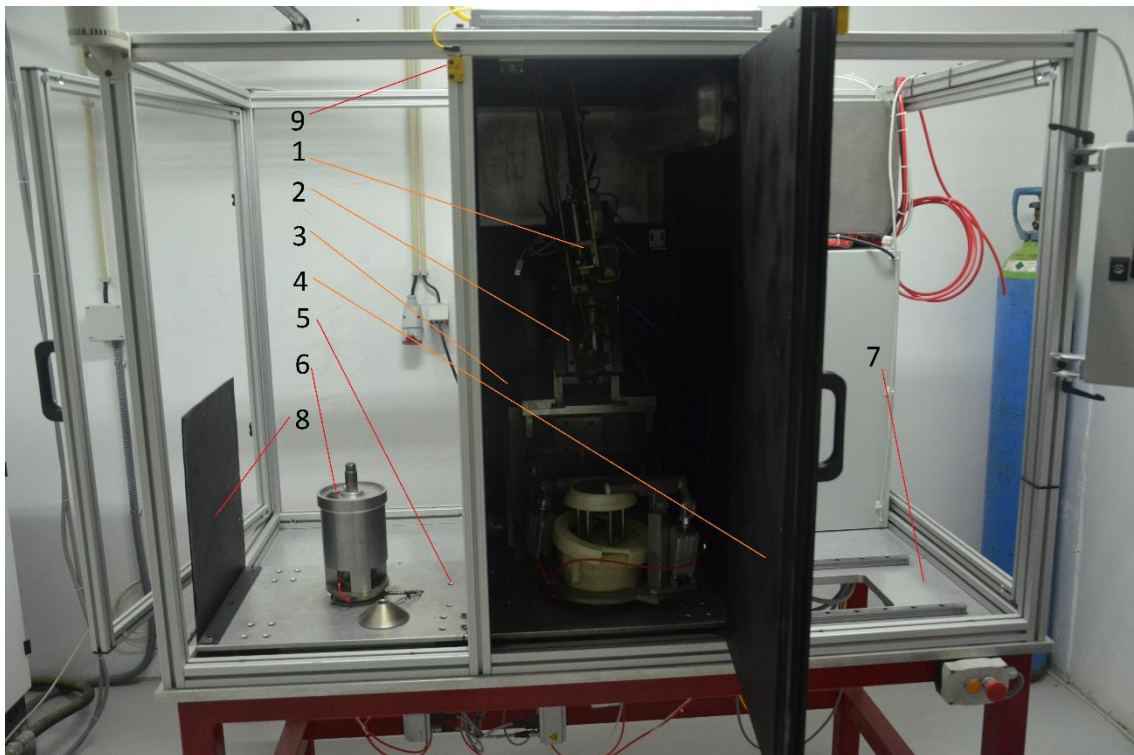


Fig 2.2 Actual view of welding station.

2.1.3 Comparison of laser beam protection methods

Laser used in industry are classified in groups and describe by international organizations: IEC, ANSI, CDRH [XII]. Classifications are based on the physical parameters of laser risk-related. Our unit fulfills conditions to be placed in the most dangerous classes, regardless which class we use for description. For example, ANSI Z136.1 defines 5 classes: 1, 2, 3a, 3b, and 4. Class 3b includes all lasers that emits average power above 500 mW, has a wavelength between 1,4 μm to 1 mm, etc. Class 4 includes all lasers having higher average power. That is why our unit (emitting 3000 times bigger power than limit defined by class 3) belongs to class 4. Contact with laser light having this power may cause cataract, skin burns and retinal photochemical and thermal burns [III].

Methods of protection against laser beam can be divided in three sections: information, personal protection and area protection. Only methods appropriate for laser of our parameters were mentioned here.

Information

The first step to avoid unnecessary risk related to laser work is to inform any people that may find themselves in danger area. The easiest way is to place original signs and labels in visible places and entrances, that inform about presence of laser and its class. There are easily available signs made in accordance with ANSI Z136 and 535.4 [IV].

Personal protection

Protection of eyes is the most important and the easiest to apply in work with laser. Main accessories are goggles, glasses [VI] and face shields [V]. They supposed to be adjusted to λ of light and for this reason they are made of particular materials colorful glass, acryl, polycarbonate, etc. Skin protection is recommended in case of I_p greater than 100 W/cm^2 [2].

The most required are heavy wool and flannel materials, which transmit only under 1% of radiation, poplin is considered as even better. Nylon based coats shouldn't be wear because of high (up to 40%) transmission.

Area protection

For protection of bigger fields special barriers and curtains, made of heavy duty, single or multi-layer fabrics or aluminum panels with special coats are being used in industry. However, the greatest surface power intensities they can be applicable with are not higher than 10000 W/cm^2 [IV][V][VI][VII][VIII][IX]. According to Table 2.2 even in distance of 10 meters surface power intensity is much bigger than maximum protection they can assure. Protective windows, separated in classes in accordance with their OD are often used to protect human eyes. For λ equal to 10600 nm, acryl is usually applied with OD 6+, which means that only 10^{-6} of total photons amount can go thru it (this is decimal logarithm of amount of light before and after reaching the barrier ratio) [1]. This type of window was already used in front chamber doors, to monitor the process.

2.1.4 Choosing methods

Some of methods of protection, mentioned in previous subchapter had already been applied: warning tables, glasses with filters, special poplin costume. Furthermore, construction of laser manipulator and kinematic limits allow the beam to reach only the area of the welded cup and table below it which reduces the operators risk significantly. A contactor that breaks the circuit every time the front doors are open was also used. The weakest point of the whole system are wall doors, which leave gaps and are not protected with any sensor against opening them.

The team decided to apply hermetic doors, both sides of the laser chamber, moved by actuator and armed with a group of sensors bringing information about their position. That system will be added as a part of main automatic system of whole welding process.

2.2 Automatic system of hermetic doors

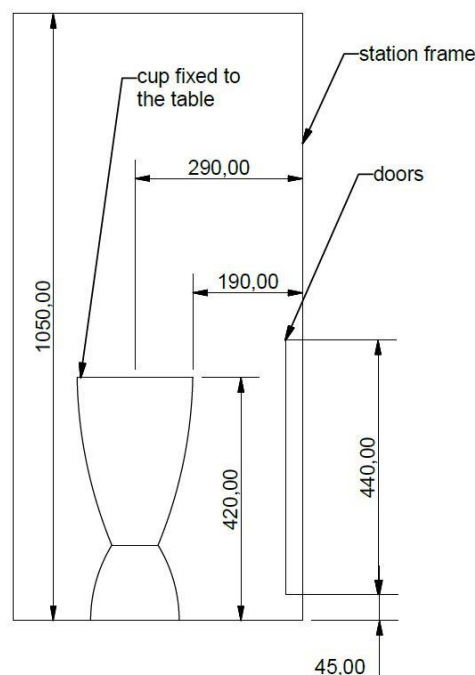


Fig 2.3 Geometrical condition for welding station (dimensions in millimeters).

2.2.1 Sketch of solution proposals

It was decided to construct a kinematic system with door, which must close the laser chamber hermetically. The system should possess one degree of freedom, be quick enough to avoid welding cycle prolongation, be a closed automatic control system, with sensors bringing feedback information. The first step was to choose the most appropriate kinematic structure. Fig 2.4 shows a group of suggested solutions:

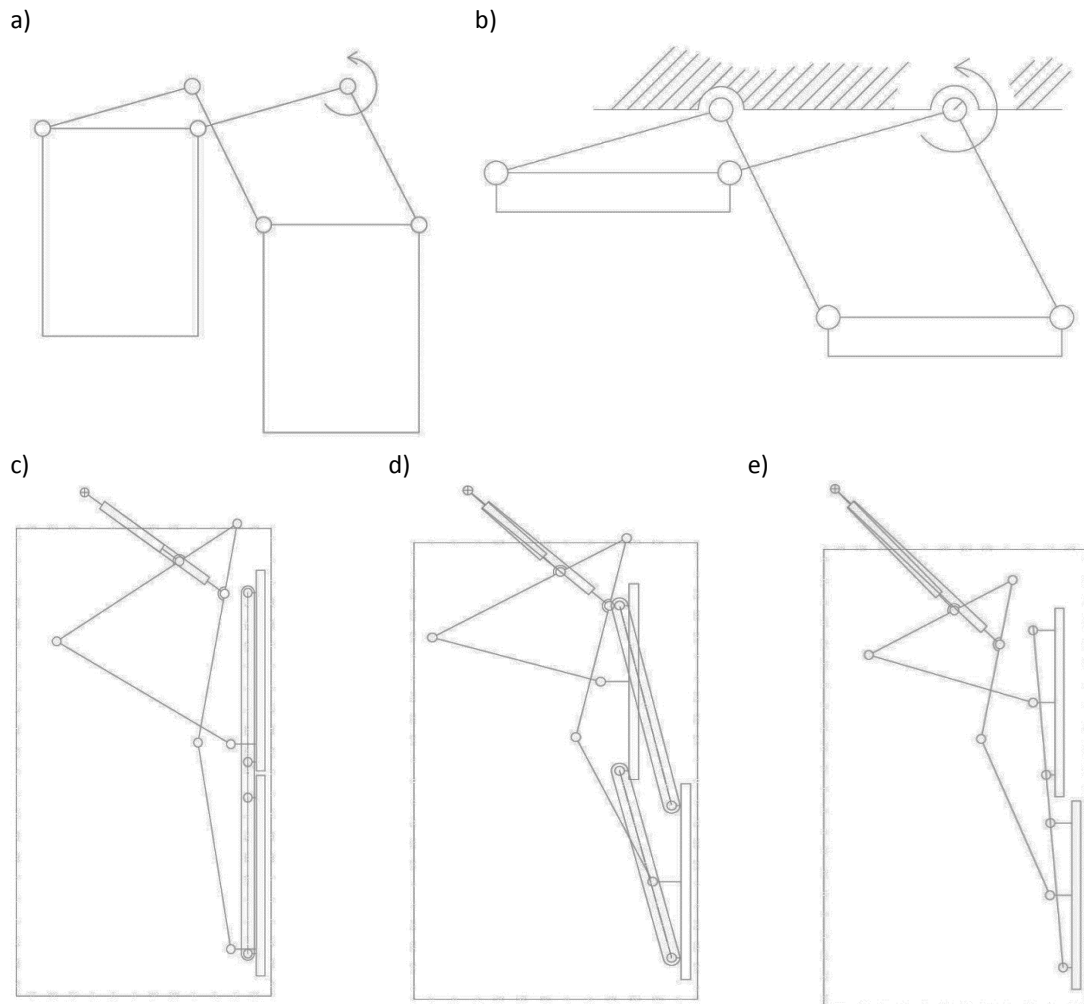


Fig 2.4 Ideas around kinematic system of doors mechanism.

Above sketches of kinematic structure were presented. The first idea, *a)* was to make doors moving in the surface parallel to the wall, that it closes. Four-bar linkage was the base of this solution. The concept, the same as shown in *c)* has one disadvantage – door coplanar with the wall makes hermetic condition difficult, taking into account necessity of use guidelines or something stabilizing the move. Solution *b)*, which only difference is making rotation move around vertical, not horizontal axis, avoids this problem, but geometrical conditions presented on Fig 2.3 are not fulfilled. Doors collides with the cup. Idea *c)* mentioned above was a new concept of changing rotating move of doors to linear. Concept *d)* was an upgrade of *c)* when the move is along a straight path not parallel to the doors surface, what eliminates problems with escape and the kinematic system doesn't collide with the cup. The final version, *e)* reduces the amount of guidelines from two to one (considering one side).

2.2.2 Kinematic system synthesis

After choosing a solution, a proper geometrical synthesis was required. Dimensions of links and position of kinematic pairs was determined by a couple of conditions, presented on Fig 2.5 and Fig 2.3:

- during normal work parts of the system must avoid a collision with the rest of the station;
- the height of doors: 430 mm;
- range of vertical move: 440 mm;
- avoid dead positions;
- angle between line of move and doors surface: 5°;
- both links possibly equal length, to let angle between points I-4, I-2, I-5 always smaller than 90°. (if 2 was much shorter part, the actuator would have to be fixed very high to be able to push the crank successfully; if 2 was much longer it could cause unresolved situation for cylinder, because during move of doors up, the piston would have to go out and in, which is impossible to apply).

For certainty the real mobility of system was checked by solving (2.5) [1]:

$$M_r = 3k - 2p_1 - p_2 = 3 * 3 - 2 * 4 - 0 = 1 \quad (2.5)$$

The system has one degree of freedom. The rest of dimensions was chosen step-by-step by creating sketch and giving constrains. The most important dimensions were shown on Fig 2.5:

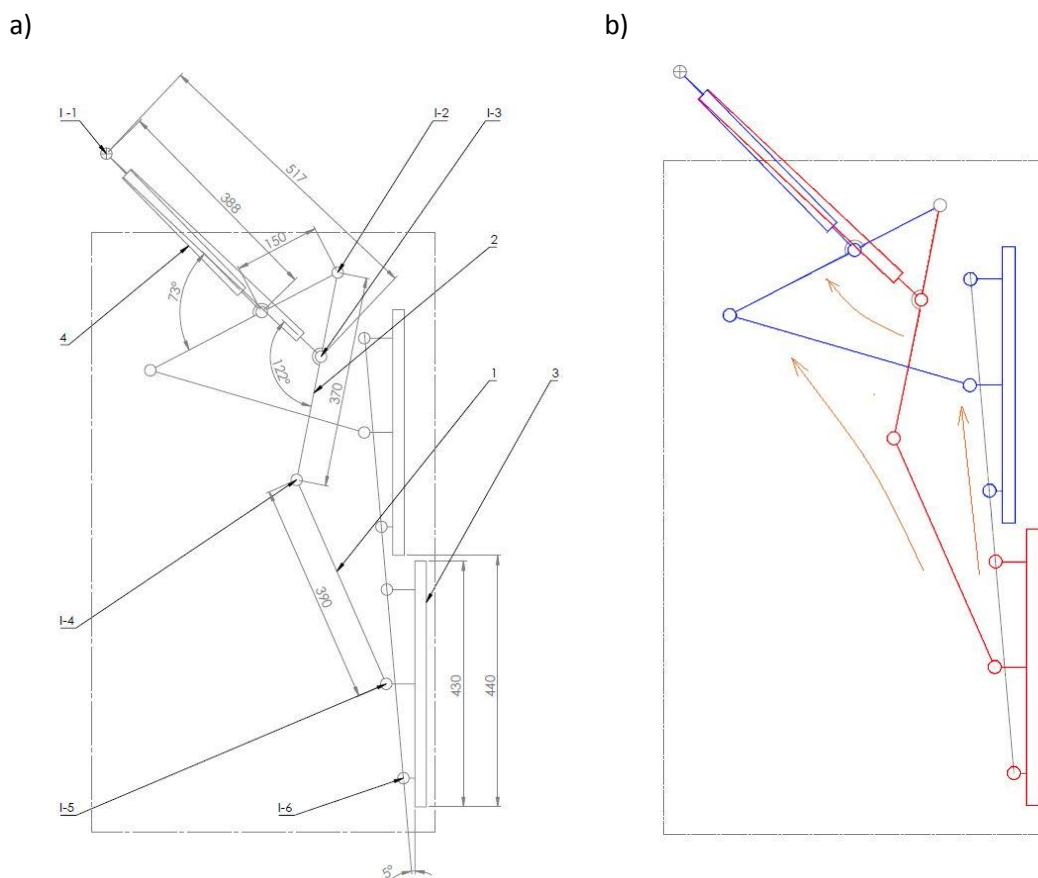


Fig 2.5 a) kinematic structure and some main dimensions; b) explanation of movement: red color – 1st position, blue color – 2nd position, brown arrows – directions of parts displacements.

The length of links (1 and 2) is equal to 390 mm and 370 mm. These are unequal because of need of avoiding collision. Pneumatic cylinder was chosen as actuator, because of easy access to pneumatic installation. Electric linear actuator was declined due to low speed and less durability. Hydraulics was also complicated application, high cost and too small forces appearing for such effort. It was decided, that the cylinder 4 will be joined with the base, and link 2 with two rotation pairs. Three more things left to be solved: diameter of the cylinder, its stroke and location. Bigger distance between $I-2$ and $I-3$ means higher momentum put to link 2, which is also related to a need of bigger stroke. Analyzing the dimensions of available cylinders the decision, about biggest stroke equal to 150 mm was taken. For effective work, a proper angle between axis of cylinder and link 2 is needed; sine of this angles should always be above 0,8. For border angles 73° and 122° make it value belonging to range of (0,84; 1) what makes the system very effective.

2.2.3 Cylinder and linear system selection

Due to necessity of proper cylinder, shafts diameter, trolleys and guidelines selection, there was a need of making simulation. A 3D modelling test using *Solidworks* software was made, retaining all geometrical properties. The aim of the animation was to solve invert kinematics, in order to find the force required to move the mechanism thru defined path in defined time. The 3D simulation was shown on Fig 2.6. Table 2.3 contains all parameters (except geometry) taken into account in this motion analysis (masses and moments of inertia were taken as maximally expected values, moments of inertia calculated in accordance to the masses and geometry).

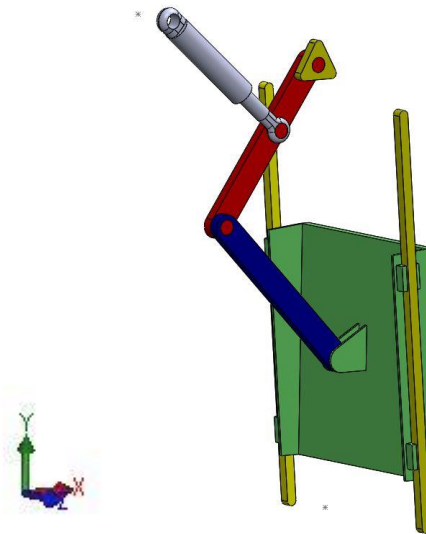


Fig 2.6 Basic 3D model for simulation needs.

Table 2.3 Parameters of structure taken for simulation

Masses and moments of inertia	
Mass of link 1 [kg]	1.0
Mass of link 2 [kg]	1.0
Mass of link 3 [kg]	5.0
Moments of inertia of link 1 (in local central coordinate systems): I_x ; I_y ; I_z [$g \cdot cm^2$]	25.7; 1492.7; 1505.3
Moments of inertia of link 2 (in local central coordinate systems): I_x ; I_y ; I_z [$g \cdot cm^2$]	24.9; 1354.7; 1340.1

Moments of inertia of link 3 (in local central coordinate systems): $I_x; I_y; I_z$ [$g \cdot cm^2$]	7523.8; 8320.0; 14842.8
Velocity of piston equation (m/s)	
$v(t) = 75\sin(2\pi/3 \cdot t)$	
Time of simulation	
$t = 3$ s	

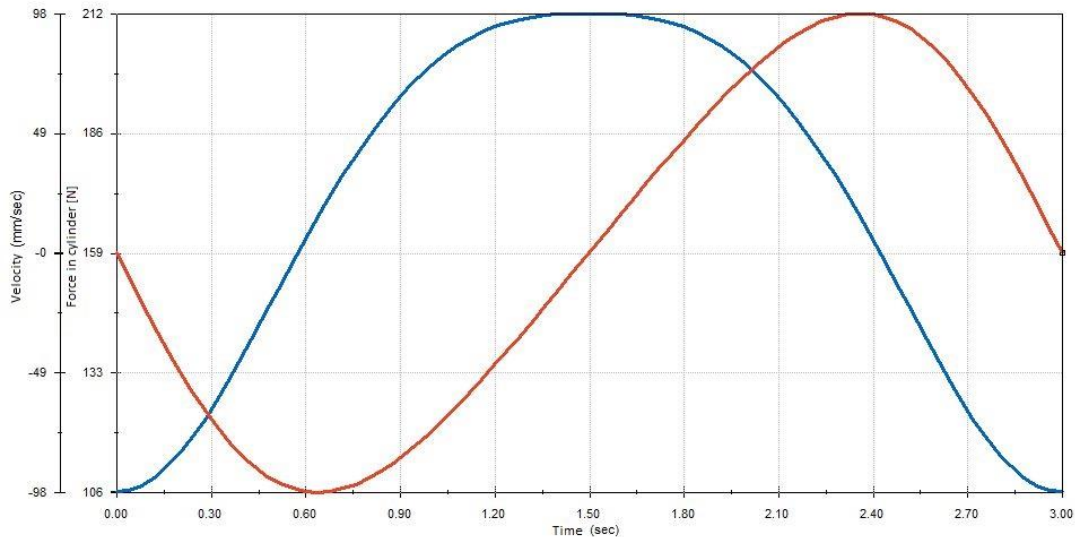


Fig 2.7 Plot presenting cylinder force (blue curve) and velocity (green curve) during single cycle of work.

Fig 2.7 presents the curves describing values of force appearing in cylinder (motor) required to receive proper dynamics of structure and linear velocity of piston rod as well. It's easy to see that the absolute extreme value is below 212 N. Normally operating pressure in industry installations is equal to 6 Bars (0,1 MPa). The diameter of piston rod is usually around 40% of the diameter of gas chamber [8][4]. The diameter of piston was approximated as solution of equation (2.6):

$$A = \frac{F}{p} \rightarrow \frac{\pi(D^2 - d^2)}{4} = \frac{F}{p} \rightarrow \frac{\pi(D^2 - (0,4D)^2)}{4} = \frac{F}{p} \rightarrow D = \sqrt{\frac{F}{\pi p * 0,21}}$$

$$D = \sqrt{\frac{212}{3,14 * 0,6 * 10^6 * 0,21}} = 0,0231 \text{ m} = 23,1 \text{ mm} \quad (2.6)$$

Finally the team decided to use a cylinder, being a product of *Festo* company: DSNU-50-150-P (Fig 2.8 a)) [6], which has possibility to be fixed in two rotating kinematic joints. The piston has cylinders diameter equal to 50 mm, what is over twice bigger that required calculated value, but assures longer life of cylinder.

a)



b)



Fig 2.8 Pictures of DSNU-50-150-P and HG-15C.

The further purchasing product was linear guideline system. As a supplier, the team chose HIWIN company, and their product: trolleys HG-15C (Fig 2.8 b)). To be sure that a single pair of trolleys can be enough for proper work, there was a need to calculate the moment of force working on single trolley in the axis parallel to I-5 rotating joint. Fig 2.9 presents forces in all 5 rotational kinematic pairs.

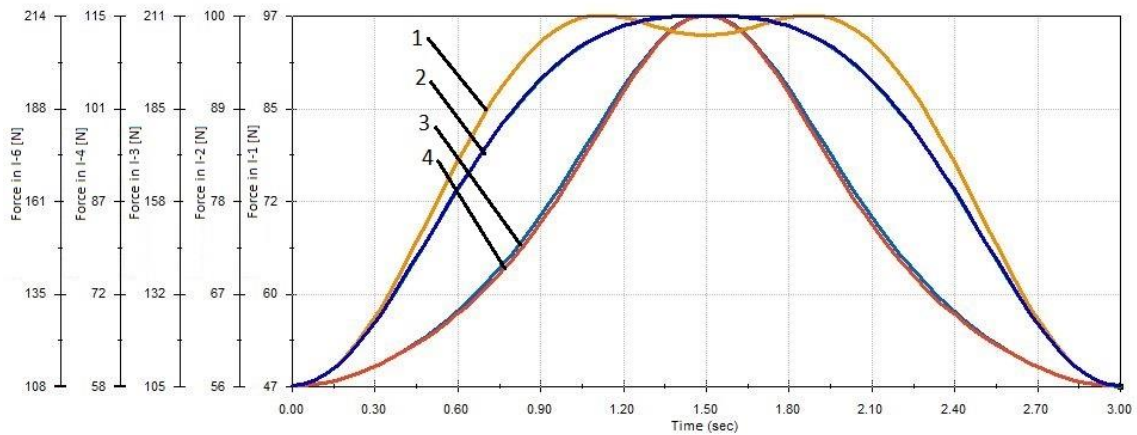


Fig 2.9 Curves presenting values of forces in kinematic joints.

(The arm of force: $r = 120 \text{ mm}$, and the force was taken as half of maximum force in the cycle:

$$M_z = \frac{1}{2} * F * r = \frac{1}{2} * 97 \text{ N} * 120 \text{ mm} = 5,82 \text{ Nm} < M_{z(0)} \quad (2.7)$$

$M_{z(0)}$ is the greatest acceptable moment of force per one trolley equal to 67 Nm [5]. That was certain, that a single pair of trolleys is absolutely enough for required conditions.

2.2.4 Construction solutions overview

Linear move of doors was made with a pair of guidelines (Fig 2.10 a)), where trolleys are fixed to movable doors and guidelines are mounted to the walls of laser chamber, furthermore because of low angular velocities, constructor decided to not apply ball-bearing, which requires more complicated housings. Instead of them, sliding sleeves were used. A single kinematic pair contains two parts. One of them has a shaft, which is put into holes in plates on both sides (Fig 2.10 b)). Tight fit doesn't allow the shaft to slide, but extra security: a pair of spacers and screws makes it insensitive to axial forces.

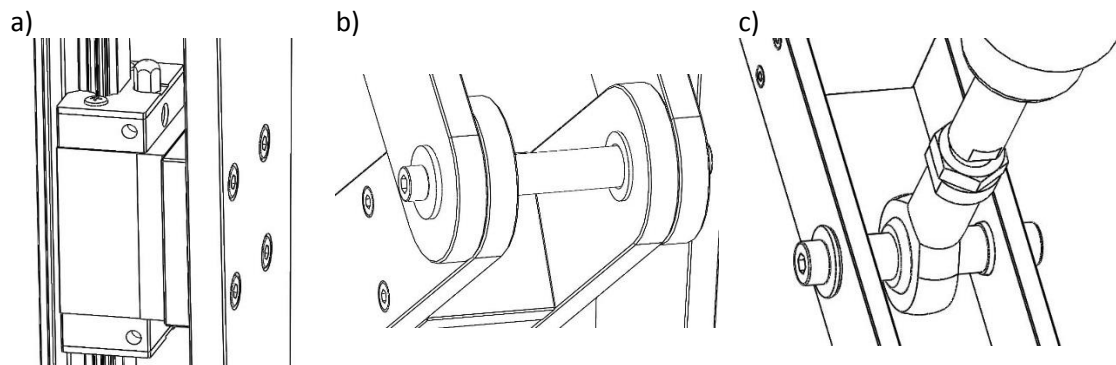


Fig 2.10 Some construction solutions applied in project (part. I).

Links 1 and 2 have simple, aluminum construction. They are made as pairs of parallel plates (Fig 2.11 a)), 8 mm thickness. For higher stiffness another pair of plates, parallel to the first one was

added ($10 \times 40 \times 50/66 \text{ mm}^3$). This construction is very low cost, easy to manufacture and suitable for mechanism requirements.

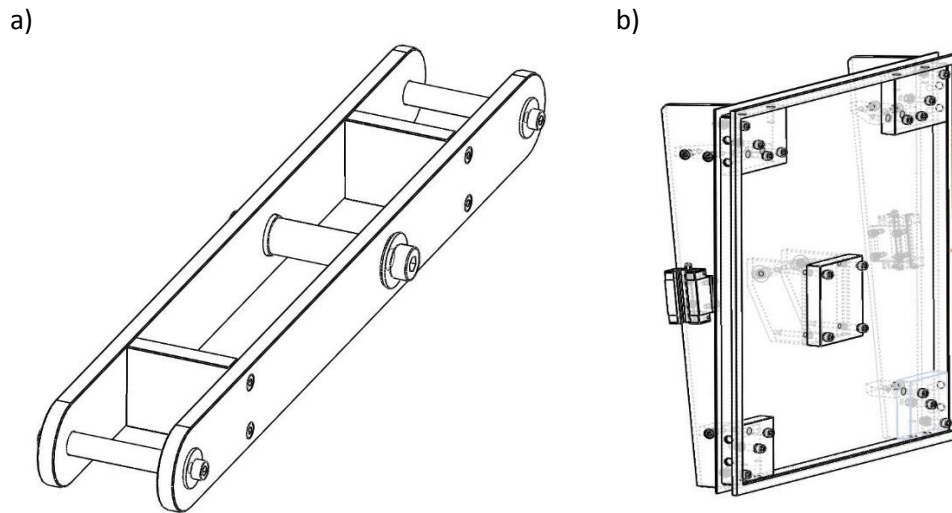


Fig 2.11 Some construction solutions applied in project (part. II).

Doors (Fig 2.11 *b*)) were designed as a pair of steel, 2 mm plates, with air gap between them. These plates are fixed together with four aluminum parts, which are supported by the brackets, that join arms of doors (with trolleys on them) together. Very important part of doors is a rubber frame, that make the whole system hermetic.

2.2.5 Strength analysis

Taking into account a range of force values, the only value that requires strength analysis is diameter of each shaft. Shafts will be made of construction steel with R_p not lower than 200 MPa. Considering properties of fatigue limits z_s was taken as 2.5. The type of load working on shaft is bending moment. The d of shaft was calculated using equation (2.8) [7].

$$d = \sqrt[3]{\frac{10 * P * r}{z_s * R_p}} = \sqrt[3]{\frac{10 * 215 \text{ N} * 0,05 \text{ m}}{2,5 * 200 \text{ MPa}}} = 5,84 \text{ mm} \quad (2.8)$$

For constructing reasons all applied diameters were equal to 12 mm. Figure shows a complete 3D model of the automatic closing doors (only parts that weren't in previous version of machine).



Fig 2.12 Render image of whole 3D model of automatic doors.

2.2.6 Pneumatic system for cylinder control and sensors for process control

DSNU-50-150-P is a cylinder having single piston rod. It will be supplied compressed air from 6 bars installation. Due to need of proper pressure regulation in both chambers it needs electro valves with supply operating voltage [0;10] V range (standard for most of industry PLC controllers). The main part of pneumatic installation (Fig 2.13 a)) contains a pair of throttling-check valves (2), a single 5/2 electro valve (3) to control direction of air flow from compressed air source (5). The outputs of these valves are may be connected to noise silencers (4) (optionally).

For higher security, the team made a decision about applying a group of inductive proximity sensors for detection steel parts of doors. They will be set in places showed in Fig 2.13 b), and their role is to send information about doors location. Table 2.4 describes information that they bring being in particular states. *IQ08-04NPOKW2S*, made by *Sick* company, was chosen as proximity sensor. It is capable to detect any metallic piece in 4 mm range, 10 to 30 VDC supply voltage, vibration-proof, made in accordance with EN-60947-5-2 (Fig 2.13 c)) [1].

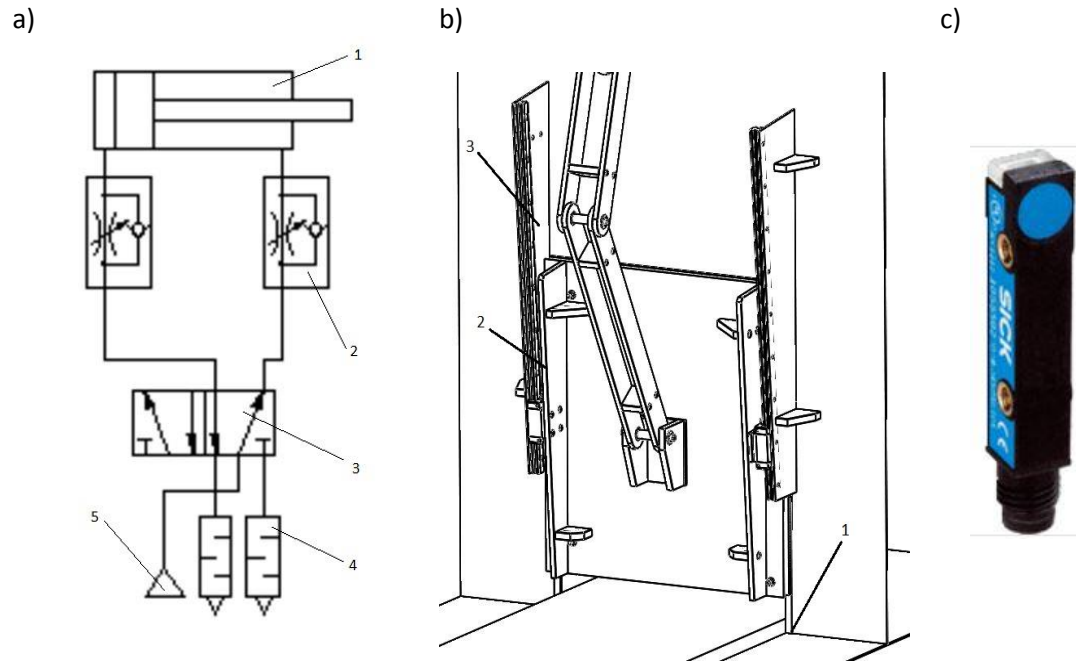


Fig 2.13 a) pneumatic installation of cylinder, b) sensors location, c) IQ08-04NPOKW25

Table 2.4 Table of sensor binary states and information that they bring.

sen. 1	sen. 2	sen. 3	information
0	0	0	Doors up, the table can move safely, stop the cylinder
0	0	1	Not possible
0	1	0	Start slower-move mode
1	0	0	Not possible
0	1	1	If previous state was (0,1,0) then go up in normal move mode; If previous state was (0,0,1) then go down in normal-move mode
1	0	1	Not possible
1	1	0	Doors closed, start welding process
1	1	1	Not possible

2.3 Summary

The main difficulty of this protection system design was a need of adjustment to existing machine, mainly its geometrical properties. Secure system, presented above is simple, mechanical parts are very easy to manufacture with a milling machine and a lathe. There is an easy access to purchasing parts made in accordance with European norms. When assembled and programmed, the system will be hermetic and resistant to any unpredicted behaviors. After finishing the 3D model, all parts were fully defined on 2D drawings. The full description of dimensioning of tolerating of parts will be described in Part II.

3. Balancing rotor of the machine

3.1 Case characteristics

3.1.1 Rotor as a part of electric power motor

Electric power three-phase motors use electric energy to produce mechanical energy. Two main parts of typical motor are stator, fixed to the base of machine and rotor. Current flowing through coils makes electromagnetic, rotating field. Rotor, movable part, is also supplied with electric energy. If rotor, with current flowing through it finds place in variable electromagnetic field, according to Lorentz law, electromagnetic force appears, which causes angular move of rotor around the axis, being center of symmetry of the machine [8].

3.1.2 Description of case

Kitchen robot, which is a product of *PR* has built-in electric power three-phase motor to rotate the blades system. The rotor is made of 60 steel plates, 0.5 mm thickness, and it possess starry symmetry, six-armed (Fig 3.1). It can reach high rotational speed up to 11000 rpm.

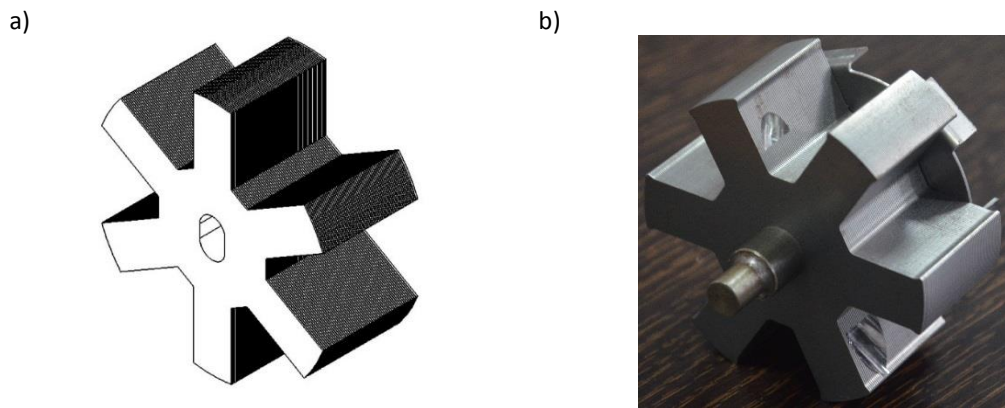


Fig 3.1 a) Model of a rotor; b) picture of real part.

The entire rotating assembly is fixed to the rest of machine by a pair of ball bearings. High-speed rotating mass can work properly only in case of very high balance. Values of dynamic reactions in bearings can be calculated with (3.1). [9]:

$$\begin{aligned}
 R_{Ax} + R_{Bx} &= m(-\omega^2 x_C - \varepsilon y_C) \\
 R_{Ay} + R_{By} &= m(-\omega^2 y_C + \varepsilon x_C) \\
 R_{Ay}b - R_{By}c &= I_{yz} \omega^2 - I_{xz} \varepsilon \\
 -R_{Ax}b + R_{Bx}c &= -I_{xz} \omega^2 - I_{yz} \varepsilon
 \end{aligned} \tag{3.1}$$

where:

- $R_{ax}, R_{bx}, R_{ay}, R_{by}$ – coordinates of vectors of reaction forces in bearings [N];
- m – mass of the object [kg];
- ω – angular velocity [rad/s];
- ε – angular acceleration [rad/s²];
- x_C, y_C – coordinates of center of gravity [m];
- I_{xz}, I_{yz} – product moments of inertia [kg*m²].

Values of b and c are the distances between support and the center of coordinate system. It can be seen in equation above, that even if the center of mass is directly on the axis of rotation dynamic forces may appear is the product moments of inertia given by equations are not equals zero (3.2).

$$I_{xz} = \iint xzdm; I_{yz} = \iint yzdm \quad (3.2)$$

Assuming, to have fully balanced rotor, the center of mass must be on the axis of rotation and both product moments of inertia must have zero values.

Unbalanced rotor was diagnosed as a source of strong vibrations. To measure range of imbalance a special balancing machine (Fig 3.2), *ND B012 Digital balancing machine* by *Nide* company was applied. The problem to solve was clear: possessing a knowledge given by machine, reduce imbalance as much as possible.

a)



b)



Fig 3.2 *ND B012 Digital balancing machine*: balancing machine a) front panel; b) mechanical equipment.

3.2 Solution

3.2.1 Inputs and measured values interpretation

Balancer needs a group of inputs for proper measuring and returns outputs. Inputs are as follows:

- A - length of the examined part [mm];
- b, c - distances between both ends of part and supports [mm];
- c' – constant value that allows used to calculate the value of material to remove equal $0,3 g \cdot mm/kg$;
- n_0 - and number of arms (for example if the examined part is a gear, this amount is a number of teeth of this gear).
- m – mass of examined object [kg]

As output the machine returns:

- p_1, p_2 – (*position*) angular location of vector of force appearing in support;

- div_1, div_2 – (value deviation) deviation value 1 and 2, which are amplitudes of dynamic reactions appearing in supports divided with square of angular velocity and multiplied by constant c' .

The p_1, p_2 values can be between 0 and number of arms (with one decimal place). Machine sets zero point as the tooth which has glued reflective tape (the beam of light is reflected by the type and comes back to light sensor). For better understanding div_1 and div_2 parameters please look at Fig 3.3. When the measured part is rotating with constant velocity, a force appears, which is proportional to square of the angular velocity. The output values are amplitudes of forces in bearings, divided by the only thing that can be variable during work – square of velocity, and multiplied with constant value c' .

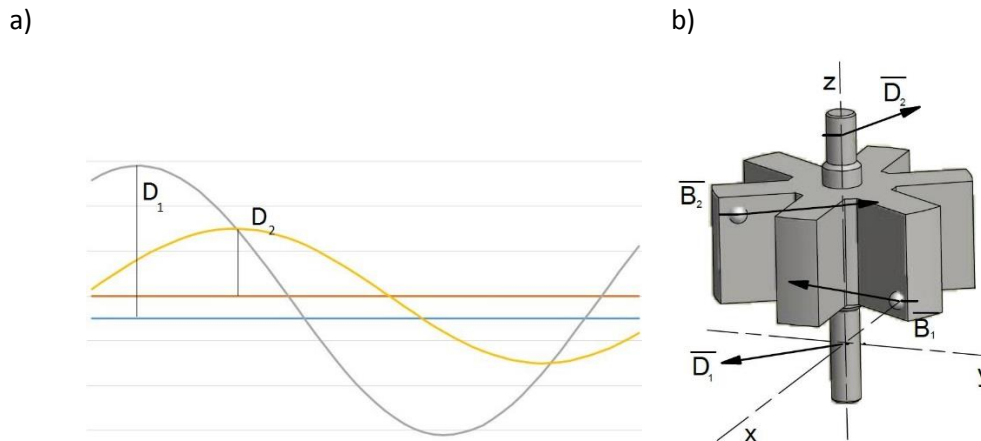


Fig 3.3 a) Dynamic reactions in bearings: a) curves describing amplitudes, b) view of vectors of reactions on rotor.

3.2.2 Method of balancing

To minimize imbalance only two things can be done: adding material on or reducing material on opposite side of axis. Methods related to add material were not satisfying. Surface welding was impossible because of unavailable equipment. High values of ω mean big centrifugal force, what makes gluing an unstable solution. Applying screws to multi-plated, bounded structure could destroy alignment of the assembly. On the other hand, removing material seemed to be better solution without those disadvantages. To this process milling machine was used. With having all output data the only thing to do was making mathematical model and manual for operator who can read values from balancer and set proper values of tool position on milling machine.

First step was the mass and location of material to remove. Our target is: new amplitudes of forces in bearings equal zeros:

$$R'_1 = R'_2 \quad (3.3)$$

We must be aware of that removing some material will cause appearing negative inertial forces working on line which connects location of removing (white points) and z-axis (see Fig 3.3), and which can be expressed with equation (3.4), where r_1, r_2 are distances between those points and z-axis:

$$B_1 = \Delta m_1 \omega^2 r_1 = b_1 \omega^2; B_2 = \Delta m_2 \omega^2 r_2 = b_2 \omega^2 \quad (3.4)$$

Our need is to know b_1 and b_2 , taking into account, that “old” reactions in bearing are equal to:

$$\mathbf{R}_1 = \mathbf{d}_1\omega^2; \mathbf{R}_2 = \mathbf{d}_2\omega^2 \quad (3.5)$$

To find values: $\mathbf{B}_1, \mathbf{B}_2$ which means four variables: $B_{1x}, B_{1y}, B_{2x}, B_{2y}$ four equations are needed. It was decided that the coordinates of points where is removed in z-axis are equal: $l_1 = 20 \text{ mm}, l_2 = 40 \text{ mm}$ and the distance between supports (bearings) is equal to $l_1 = 60 \text{ mm}$. Equations below represent conditions of zero forces in bearings:

$$\begin{aligned} \sum \mathbf{P} &= \mathbf{B}_1 + \mathbf{B}_2 + \mathbf{R}_1 + \mathbf{R}_2 = 0 \\ \sum \mathbf{M}_1 &= \mathbf{B}_1 l_1 + \mathbf{B}_2 l_{12} + \mathbf{R}_2 L = 0 \end{aligned} \quad (3.6)$$

Solution of these equations and using all substitutions we achieved:

$$\begin{aligned} b_{1x} &= -2d_{1x} + d_{2x} = -2d_1 \cos\alpha_1 + d_2 \cos\alpha_2 = -2d_1 c_1 + d_2 c_2 \\ b_{1y} &= -2d_{1y} + d_{2y} = -2d_1 \sin\alpha_1 + d_2 \sin\alpha_2 = -2d_1 s_1 + d_2 s_2 \\ b_{2x} &= d_{1x} - 2d_{2x} = d_1 \cos\alpha_1 - 2d_2 \cos\alpha_2 = d_1 c_1 - 2d_2 c_2 \\ b_{2y} &= d_{1y} - 2d_{2y} = d_1 s_1 - 2d_2 s_2 \end{aligned} \quad (3.7)$$

Here $\alpha_1 = p_1 * 60^\circ$ and $\alpha_2 = p_2 * 60^\circ$. It is easy to see, that so far operator only needs to calculate very simple equations to find $b_{1x}, b_{1y}, b_{2x}, b_{2y}$. Values of sines and cosines can be found in table in the station.

Also angular locations: β_1, β_2 needs to be found with using inverse trigonometric functions:

$$\begin{aligned} b_{1x} > 0, b_{1y} > 0 &\rightarrow \beta_1 = \text{atan}\left(\frac{b_{1y}}{b_{1x}}\right) \\ b_{1x} < 0 &\rightarrow \beta_1 = \text{atan}\left(\frac{b_{1y}}{b_{1x}}\right) + 180^\circ \\ b_{1x} > 0, b_{1y} < 0 &\rightarrow \beta_1 = \text{atan}\left(\frac{b_{1y}}{b_{1x}}\right) + 360^\circ \end{aligned} \quad (3.8)$$

The same equations are applicable for β_2 . To find e_1, e_2 – masses of material to remove multiplied by distance to z-axis, and from which arm: a_1, a_2 remove the material, last four equations must be solved:

$$\begin{aligned} e_1 &= \sqrt{b_{1x}^2 + b_{1y}^2} \\ e_2 &= \sqrt{b_{2x}^2 + b_{2y}^2} \\ a_1 &= \frac{\beta_1}{60^\circ} \\ a_2 &= \frac{\beta_2}{60^\circ} \end{aligned} \quad (3.9)$$

For easy use of data, an operator will not have to solve all those equations. The manual for the station will be introduced at the end of the section.

3.2.3 Searching precise milling parameters

The aim of the analysis described in this subchapter was to create the simplest model of removing material on milling machine with the biggest precision and manual for the worker as well. It was decided, that material will be removed by end mill, $\Phi 9$ diameter on one side of the tooth as shown on Fig 3.4:

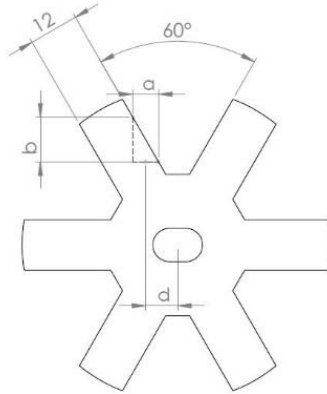


Fig 3.4 Geometrical properties of the rotor and values used during milling.

It is easy to see that milling this way possesses a couple of parameters. Some of them was set as constant: $d = 7$ mm, and b/a ratio, which is equal to $\sqrt{3}$ (rotor will always be set on milling machine table with two arms parallel to the table surface). Operating b value we can remove some volume of material which is equal to the volume of cylinder cut by plane orientated 60° to its base (which diameter is equal to the diameter of the tool – 9 mm) and height of b . The main difficulty was to find equation describing mass of cut cylinder (m) and coordinate of the center of mass perpendicular to rotation axis [10]. Integrating, the function described in was found:

$$V = f(b) = 2\rho \int_{\frac{9}{2} - \frac{b}{\sqrt{3}}}^{\frac{9}{2}} dx \int_0^{\sqrt{\frac{81}{4} - y^2}} dy \int_0^{\frac{y\sqrt{3}}{3} + b - \frac{3\sqrt{3}}{2}} dz \quad (3.10)$$

$$c_b = g(b) = 3 + 7\sqrt{3} - \frac{b}{2} + \frac{1}{b} \int_0^b zdz \int_{-\frac{9}{2}}^{9 + \frac{\sqrt{3}}{3}(z-b)} 2dx \int_0^{\sqrt{\frac{81}{4} - x^2}} dy$$

Furthermore:

$$\Delta mr_g = c_b m = h(b) \quad (3.11)$$

The solution of integrating is so extensive, that there was no sense of typing it in the document, what is more, the function, that is really needed is:

$$h^{-1}(\Delta mr_g) = b \quad (3.12)$$

That was impossible to do with analytic methods, which is why the function was estimated:

$$h^{-1}(\Delta mr_g) = -5E-10\Delta mr_g^6 + 2E-07\Delta mr_g^5 - 2E-05\Delta mr_g^4 + 0,0013\Delta mr_g^3 - 0,0416\Delta mr_g^2 + 0,7616\Delta mr_g + 0,6519 \quad (3.13)$$

3.3 Manual for operator

Following those steps an operator supposed to successfully calculate all values needed and find out all parameters of milling. We will show it on example values taken from machine. All calculated values will be written in Table 3.5.

- 1) Read values: $div_1=114$, $div_2=342$, and immediately multiply them with 0,175 (mass of object multiplied by constant c') coefficient to receive $d_1=20$, $d_2=60$, read $p_1=0.5$, $p_2=3.5$.
- 2) For $p_1=0.5$, $p_2=1.4$ find in
- 3)
- 4) Table 3.1 values of $c_1=0.866$, $s_1=0.500$, $c_2=-0.866$, $s_2=-0.500$.

Table 3.1 Vales of sine and cosine function.

p	c	s	p	c	s	p	c	s
0,0	1,000	0,000	2	-0,500	0,866	4	-0,500	-0,866
0,1	0,995	0,105	2,1	-0,588	0,809	4,1	-0,407	-0,913
0,2	0,978	0,208	2,2	-0,669	0,743	4,2	-0,309	-0,951
0,3	0,951	0,309	2,3	-0,743	0,669	4,3	-0,208	-0,978
0,4	0,914	0,407	2,4	-0,809	0,588	4,4	-0,105	-0,995
0,5	0,866	0,500	2,5	-0,866	0,500	4,5	0,000	-1,000
0,6	0,809	0,588	2,6	-0,914	0,407	4,6	0,104	-0,995
0,7	0,743	0,669	2,7	-0,951	0,309	4,7	0,208	-0,978
0,8	0,669	0,743	2,8	-0,978	0,208	4,8	0,309	-0,951
0,9	0,588	0,809	2,9	-0,995	0,105	4,9	0,407	-0,914
1,0	0,500	0,866	3	-1,000	0,000	5	0,500	-0,866
1,1	0,407	0,914	3,1	-0,995	-0,104	5,1	0,588	-0,809
1,2	0,309	0,951	3,2	-0,978	-0,208	5,2	0,669	-0,743
1,3	0,208	0,978	3,3	-0,951	-0,309	5,3	0,743	-0,669
1,4	0,105	0,995	3,4	-0,914	-0,407	5,4	0,809	-0,588
1,5	0,000	1,000	3,5	-0,866	-0,500	5,5	0,866	-0,500
1,6	-0,104	0,995	3,6	-0,809	-0,588	5,6	0,913	-0,407
1,7	-0,208	0,978	3,7	-0,743	-0,669	5,7	0,951	-0,309
1,8	-0,309	0,951	3,8	-0,669	-0,743	5,8	0,978	-0,208
1,9	-0,407	0,914	3,9	-0,588	-0,809	5,9	0,995	-0,105

- 5) Using equations calculate values:

$$\begin{aligned}
 b_{1x} &= -2d_1c_1 + d_2c_2 = -86.60 \\
 b_{1y} &= -2d_1s_1 + d_2s_2 = -50.00 \\
 b_{2x} &= d_1c_1 - 2d_2c_2 = 121.24 \\
 b_{2y} &= d_1s_1 - 2d_2s_2 = 70.00
 \end{aligned}
 \tag{3.14}$$

- 6) Put signs of b_{1x} , b_{1y} , b_{2x} , b_{2y} to the table: "-","+", "+", "-".
- 7) Using equations calculate:

$$\tan_1 = \left| \frac{b_{1y}}{b_{1x}} \right| = 0.57
 \tag{3.15}$$

$$\tan_2 = \left| \frac{b_{2y}}{b_{2x}} \right| = 0.58$$

- 8) Using Table 3.2 find values a_1 and a_2 for \tan_1 and \tan_2 : $a_1 = 0.48$ and $a_2 = 0.52$

Table 3.2 Table of conversion "tan" to "a" values.

tan	a	tan	a	tan	a
0,000	0,00	0,750	0,61	2,600	1,15
0,025	0,02	0,800	0,64	3,000	1,19
0,050	0,05	0,850	0,67	3,400	1,23
0,075	0,07	0,900	0,70	3,800	1,25
0,100	0,10	0,950	0,73	4,200	1,28
0,150	0,14	1,000	0,75	5,000	1,31
0,200	0,19	1,050	0,77	6,000	1,34
0,250	0,23	1,100	0,80	7,000	1,36
0,300	0,28	1,200	0,84	8,000	1,38
0,350	0,32	1,300	0,87	10,000	1,40
0,400	0,36	1,400	0,91	12,000	1,42
0,450	0,40	1,500	0,94	15,000	1,44
0,500	0,44	1,600	0,97	20,000	1,45
0,550	0,48	1,800	1,02	30,000	1,47
0,600	0,52	2,000	1,06	50,000	1,48
0,650	0,55	2,200	1,09	100,000	1,49
0,700	0,58	2,400	1,12	200,000	1,50

- 9) Find proper values of q_1 and q_2 for yours a_1 and a_2 using table; $q_1 = 3.48$; $q_2 = 0.52$

Table 3.3 Table of signs meaning.

+	+	$q = a + 3$
-	+	$q = 6 - a$
-	-	$q = a$
+	-	$q = a + 3$

- 10) Using equations calculate:

$$\begin{aligned} e_1 &= \frac{1}{2} \sqrt{b_{1x}^2 + b_{1y}^2} = 50.01 \\ e_2 &= \frac{1}{2} \sqrt{b_{2x}^2 + b_{2y}^2} = 69.99 \end{aligned} \quad (3.16)$$

- 11) Read from the table b-parameter, as depth of milling: $b_1 = 11.18 \text{ mm}$, $b_2 = 13.54 \text{ mm}$.

Table 3.4 Table of converting "e" to "b" values.

e	b	e	b	e	b
1	1,15	17	5,96	48	10,91
2	1,71	18	6,16	50	11,18
3	2,17	20	6,55	52	11,43
4	2,57	22	6,93	54	11,69
5	2,92	24	7,29	56	11,94

6	3,25	26	7,64	58	12,18
7	3,56	28	7,97	60	12,43
8	3,84	30	8,30	63	12,79
9	4,12	32	8,62	66	13,14
10	4,38	34	8,93	69	13,48
211	4,63	36	9,23	72	13,82
12	4,87	38	9,53	75	14,15
13	5,10	40	9,81	78	14,48
14	5,33	42	10,10	82	14,91
15	5,54	44	10,37	86	15,33
16	5,76	46	10,65	90	15,74

12) Check if all values in Table 3.5 fulfilled.

Table 3.5 Table of milling parameters calculations.

Number of rotor:													
d ₁	C ₁	b _{1x}	tan ₁	a ₁	+/-	q ₁	e ₁	b ₁	arm ₁	d' ₁			
d ₂	C ₂	b _{1y}		+/-									d' ₂
p ₁	S ₁	b _{2x}	tan ₁	a ₂	+/-	q ₂	e ₂	b ₂	arm ₂	p' ₁			
p ₂	S ₂	b _{2y}		+/-									p' ₂

After passing the algorithm operator knows, that should mill in two places: first on slopes of 0 and 1 arm, 11.18 mm depth and between 3 and 4 arm, 13.54 mm depth.

3.4 Simulation

With use of all numerical data, from the example above, a simulation was made. To simulate initial imbalance to fully symmetrical model a pair of balls were added, having location and mass properties adequate values to described in previous subchapter Fig 3.5.

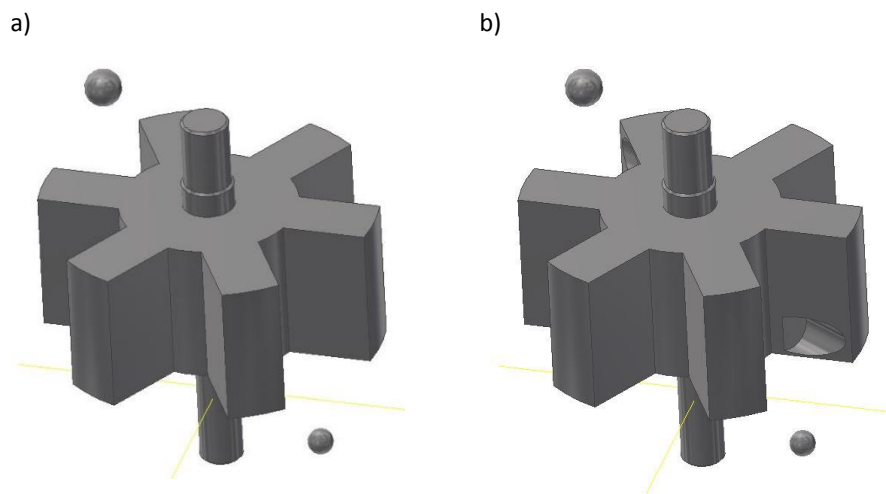


Fig 3.5 View of rotor simulation model: a) before milling, b) after milling.

Values of center of mass position and product moments of inertia are shown in Table 3.6. It is easy to see that these amounts decreased 30, 40 or 60 times to compare with initial unbalance.

Table 3.6 Values of center of mass position, product moments of inertia and forces in bearings before and after milling (11000 rpm).

	Before milling	After milling
x_c [mm]	0.060	-0.001
y_c [mm]	0.034	-0.000
I_{xz} [g*mm ²]	2.084	0.054
I_{yz} [g*mm ²]	1.203	0.028
R_1 [N]	28.2	1.35
R_2 [N]	53.2	2.07
L_1 [hours]	2.00	6.04
L_2 [hours]	2.42	5.03

3.5 Summary

Due to good balance durability of bearing can be even a few times longer. Vibration were eliminated almost totally. Operator can measure parameters of the rotor and after a couple of operations and calculations, find in which places and how deep to mill. The algorithm can be initially a bit complicated, but makes us almost sure that milling only two times can give us very high balance. Even better way is to add a computer with *.xls template to the station, where operator inserts only values after first measurement and reads milling parameters. Unfortunately this method cannot be perfect because of heterogeneous density of the material which is unpredictable. However milling can be applied more than one time in case of first trial failure.

4. Milling machine improvement

As it has been already said, rotors balancing will be done with use of conventional milling machine. The machine will be inseparable part of balancing station, which means that measuring and milling will be done by the same person. Object (the rotor) always has the same geometry, what is more, it needs to be fixed every time in the same position (one of 6 angular positions, to mill in one of its arms). That is why project manager decided to make an improvement of the machine that will allow to reduce time of work by removing standard fixing system (manually operated vice) and replacing it by sleigh or clamp driven by pneumatic cylinder. The role of operator will only be to press pneumatic pedal (by foot) during milling and releasing it after the process. Applying a cylinder has also another reason: during milling, the particular plates were bending and deforming. Fig 5.1 presents a view of milling machine (a) and damaged rotor (b)). Manually fixed part was not secured properly so the tool could damage it. That is why selected cylinder *CDQ-2B-140-30DC* by *SMC* company can generate 9,2 kN force when its supplied by 6 bars pressure.

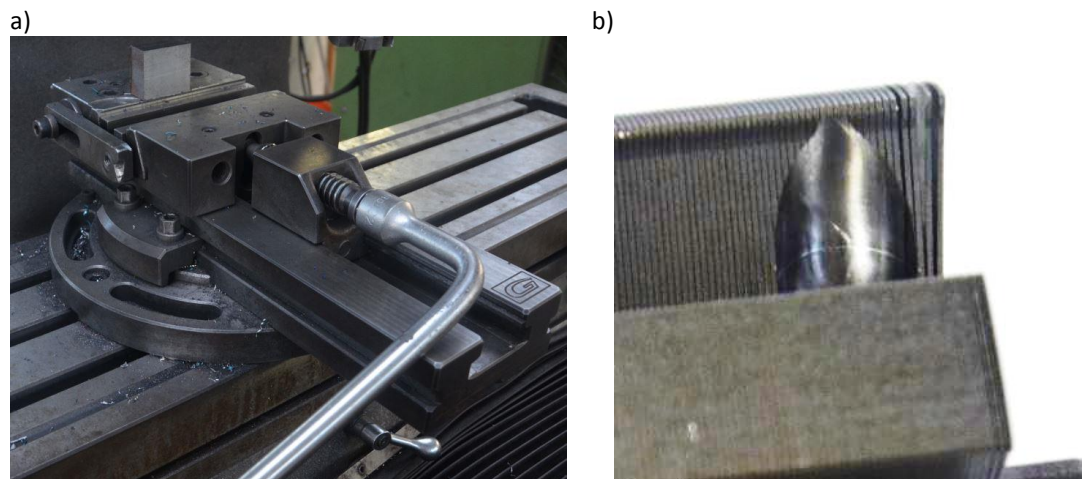


Fig 4.1 a) View of standard milling machine b) damaged rotor after milling process.

4.1 Primary concept

Primary concept of machine development is shown on Fig 4.2. Parts 1 and 2: the table and one of clamps existing in standard version of machine. The cylinder (3), is fixed with pair of plates (4,5), mounted on supporting plate (6). Pair of symmetrical parts (7, another is invisible) carry the load to the table. For bigger moments of inertia of sections perpendicular to cylinder axis another plate (8) was used. Parts 9, 10, 11 transmit energy to the sleigh (12) which also belong to original state of milling machine. Three parts were used, instead of single one, to adjust the distance between cylinder and sleigh.

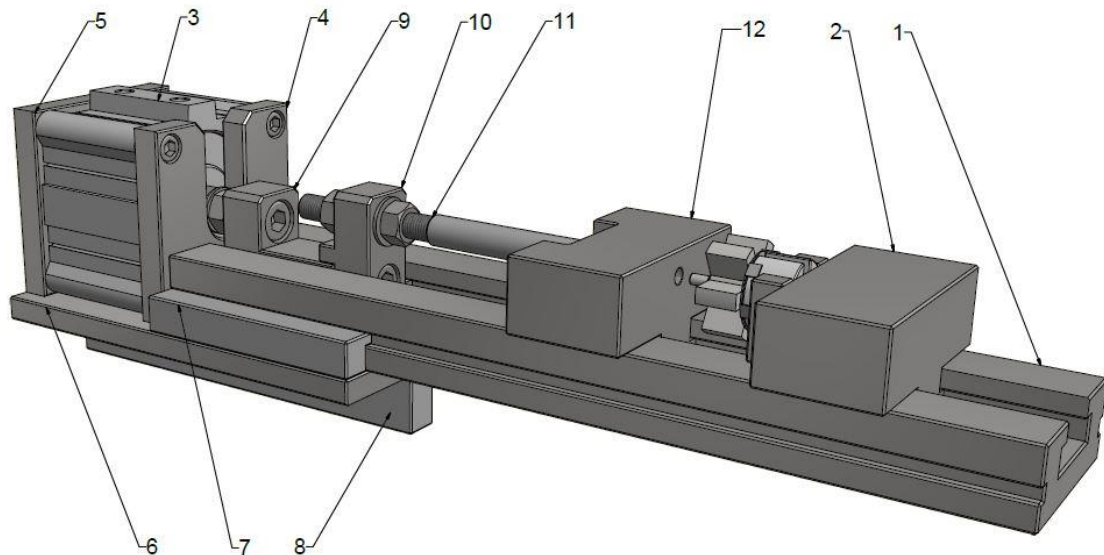


Fig 4.2 Primary concept of machine improvement.

Fig 4.3 shows the way of mounting a single rotor on the table. Part 2 is not movable and has a nest for round part 3. A rotor (1) is inserted coaxially in 3 and its crown holds external cylindrical surface of that part. That solution makes rotor to not fall there sleigh is not in contact with rotor.

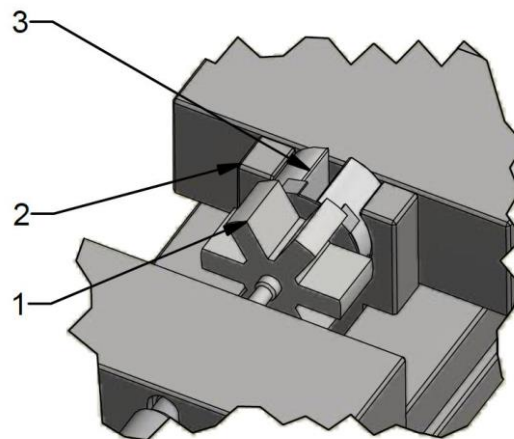


Fig 4.3 Detail view of rotor fixing.

4.2 Final concept

After discussing the solution two changes were made. Front fixing plate was replaced by pair of brackets (1, Fig 4.4) which are more resistive for loads. A pair of parts from initial solution was removed. A shaft with external thread to mount in cylinder on one side and threaded hole on another side was applied instead (2).

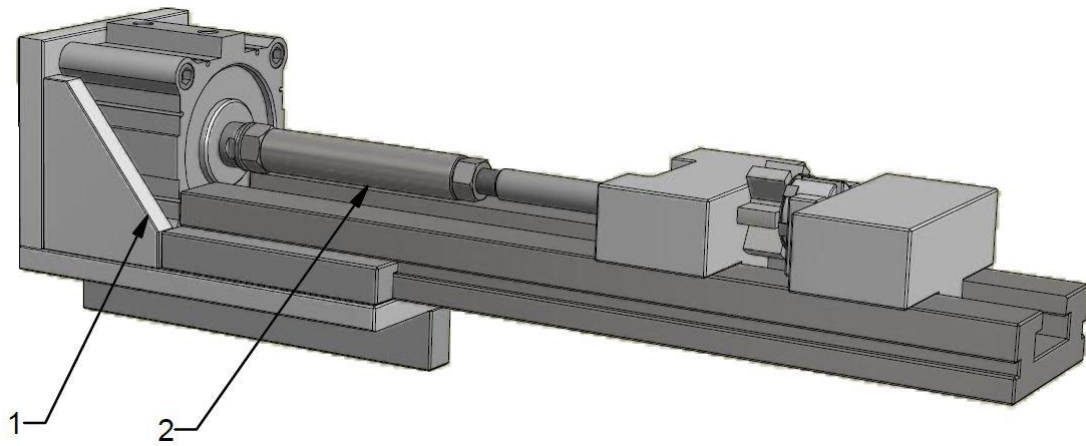


Fig 4.4 Detail view of rotor fixing.

The assembly has stiff construction, designed to bring the load from cylinder to the table. The only thing which required strength analysis is pair of shafts (connecting cylinder with sleigh). Due to axial force there is a risk of buckling. Those two parts were mathematically modeled as single shaft with diameter of 20 mm (the smallest diameter appearing along its axis). First the type of buckling: spring or inelastic [XIV]. First minimal radius of gyration (i_{min}) and slenderness were calculated:

$$i_{min} = \sqrt{\frac{I_{min}}{A}} = \sqrt{\frac{\pi * d^4 * 4}{64 * \pi * d^2}} = \frac{d}{4} = 5 \text{ mm} \quad (4.1)$$

$$\lambda = \sqrt{\frac{\mu * l}{i_{min}}} = \sqrt{\frac{0,699 * 420 \text{ mm}}{5 \text{ mm}}} = 7,66 \quad (4.2)$$

where μ is a coefficient depended on type of support. In that case (see Fig 4.5) this value is equal 0.699.

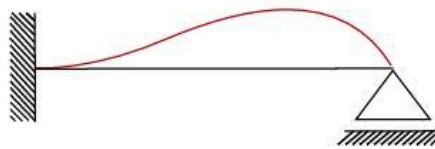


Fig 4.5. Shaft support mathematical model [XIV].

Border value of slenderness was calculated with equation:

$$\lambda_b = \pi \sqrt{\frac{E}{R_h}} = \sqrt{\frac{2 * 10^{11}}{3 * 10^8}} = 81,07 \quad (4.3)$$

That means the type of buckling is inelastic. Using Tetmajer-Jasiński's equation critical force was estimated. Constant values a and b in equation depend on material type and for steel they have values: $a = 338.7 \text{ MPa}$, $b = 1.48 \text{ MPa}$.

$$P_{kr} = A * (a - b\lambda) = \pi \left(\frac{20}{2}\right)^2 (338.7 - 1.48 * 7,66) = 102,8 \text{ kN} \quad (4.4)$$

The value of critical force is over ten times bigger than the maximum static force loading the shaft. There is no need to consider unpleasant behavior.

The construction with pneumatic cylinder was installed on machine table. Pneumatic installation was applied, including pneumatic pedal. First rotors have already been milled and plates remain not deformed.

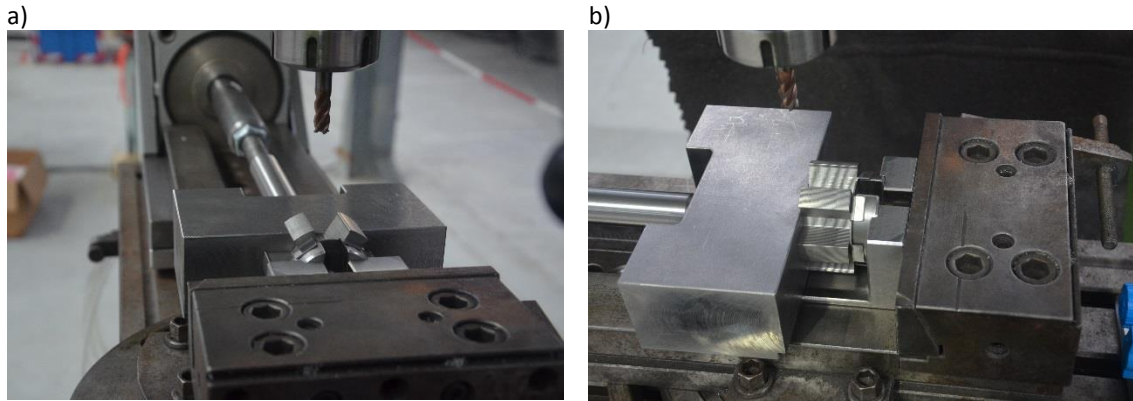


Fig 4.6 View of improved machine table.

5. Test station for electromechanical connection

5.1 Heating connector and its test

The cup of kitchen robot, which welding process was mentioned in chapter 2. contains a resistive heating plate. For generating the heat some electric current must flow through resistor to generate a heat proportional to the resistance and root mean square of this current value [11]. Users of robot will need to take out a cup in order to clearing, which means that the electronic connection must be detachable.

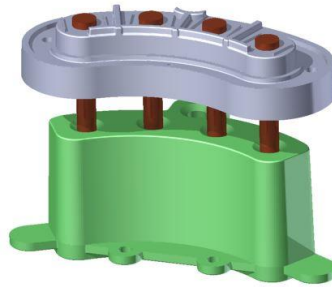


Fig 5.1 Heating connector

Fig 5.1 presents the heating connector. Upper part is normally fixed with the cup, when lower is glued to the housing of robot. Often connection and disconnection of those parts makes a need of durability tests conduction. The connection should last at least 50 000 cycles saving its mechanical and electrical properties.

5.2 Station overview

The station should simulate conditions of normal use. It was decided that bottom part must be fixed to a frame when upper will be connected to piston of cylinder, which makes move up and down. Because forces appearing during making connection are not essential, some extra guidelines for move stabilization were not necessary. Instead of them a special cylinder (*Festo, DFM-12-25-P-A-GF*), containing pair of shafts and built-in ball bearings was applied (Fig 5.2 a). [12]. The stroke of this cylinder is equal to 25 mm which is enough to mount parts and make connecting-disconnecting moves. To fix bottom part to the table quickly and securely a pair of toggle clamps, produced by *Speedyblock* was used Fig 5.2 b).

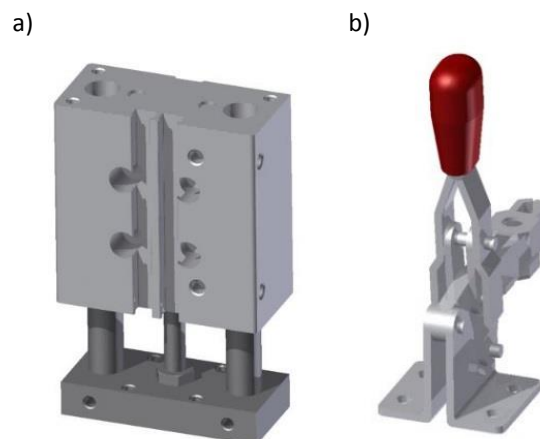


Fig 5.2 a) Pneumatic cylinder, *DFM-12-25-P-A-GF*; b) *Sauterelle 70[®]*, toggle clamps.

Fig 5.3 *a*) presents the station assembly. It contains four-parts aluminum frame (1), a cylinder (2) and a couple of toggle clamps (4). For better stabilization of bottom parts a pair of pins (7) was put into holes in connector housing (6). The most complicated shape has part 4, which must be adjusted to geometry of upper part of connection. This one required CNC machining with making a program based on 3D model. To not let the connector part fall down, a pair of small blocks (5) must be screwed to (3). Fig 5.3 *b*) shows a real station view.

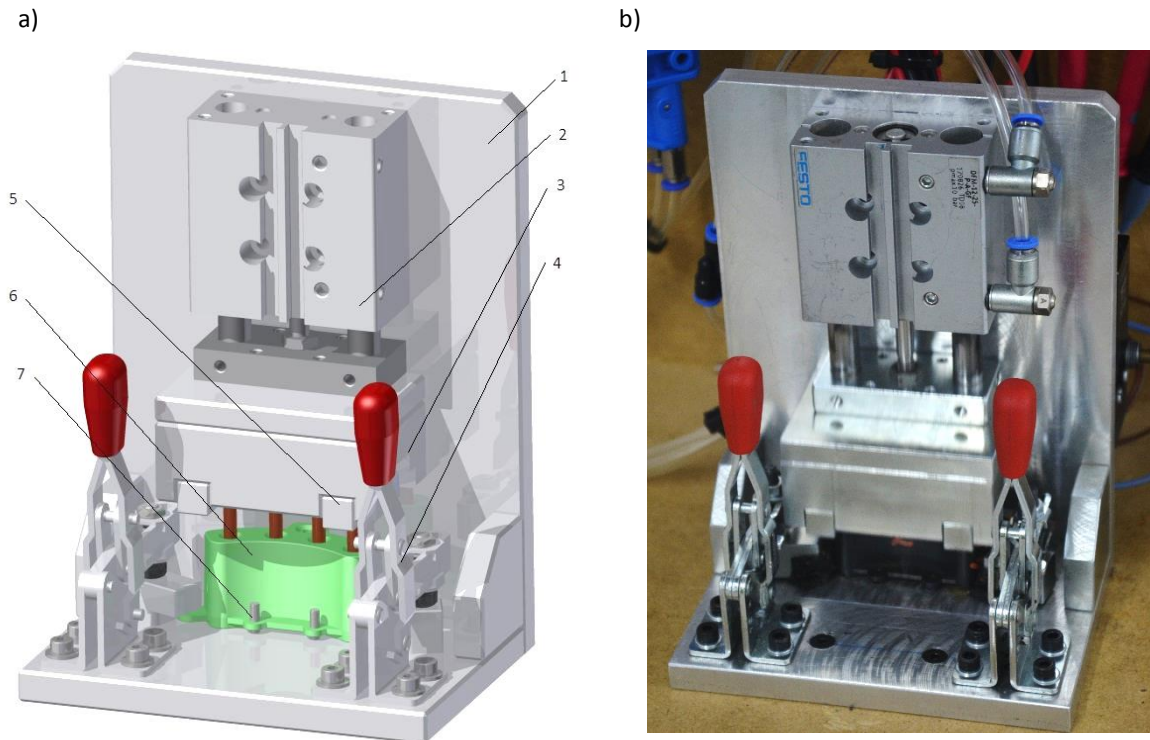


Fig 5.3 Heating connector test station: a) render of 3D model; b) view of the real station.

5.3 Pneumo-electronic system for controlling testing process

To control the process there was a need to apply some controlling unit to steer cylinder's move. Instead of applying any industry controller (for example PLC) or making an electronic circuit with microcontroller a group of special electro valves with built-in timers were used. The pneumatic system applied in the station was shown on Fig 5.4. The cylinder (1) is connected with conduits to a pair of one-way flow control valves (2) used for exhaust-air control. These valves can adjust flow speed with knurled screw. To switch direction of piston move out and in, 4/2 pressure operating valve (4) with pneumatic spring reset method [14]. Compressed air comes to the valve from external 6 bars installation. On its way the air runs through on-off, 2/2 valve (8), manually operated with soft-start system for pressurising and venting [15]. Further the air meets filter regulator possessing 40 μm filter cartridges and gauge [16]. For initializing and ending a work in loop a front panel valve with selector switch [17] was added to system. A very important part, responsible for automatic switching the flow direction via putting pressure on valve 4 is a time-delay valve (5), pressured controlled with manually adjusted delay time. A complete system can work automatically in infinite loop. After setting delay values, the only thing operator must do to make the system work is to turn on the main switch, check a pressure value on gauge, and turn on loop mode switching button in valve 6 [XVI].

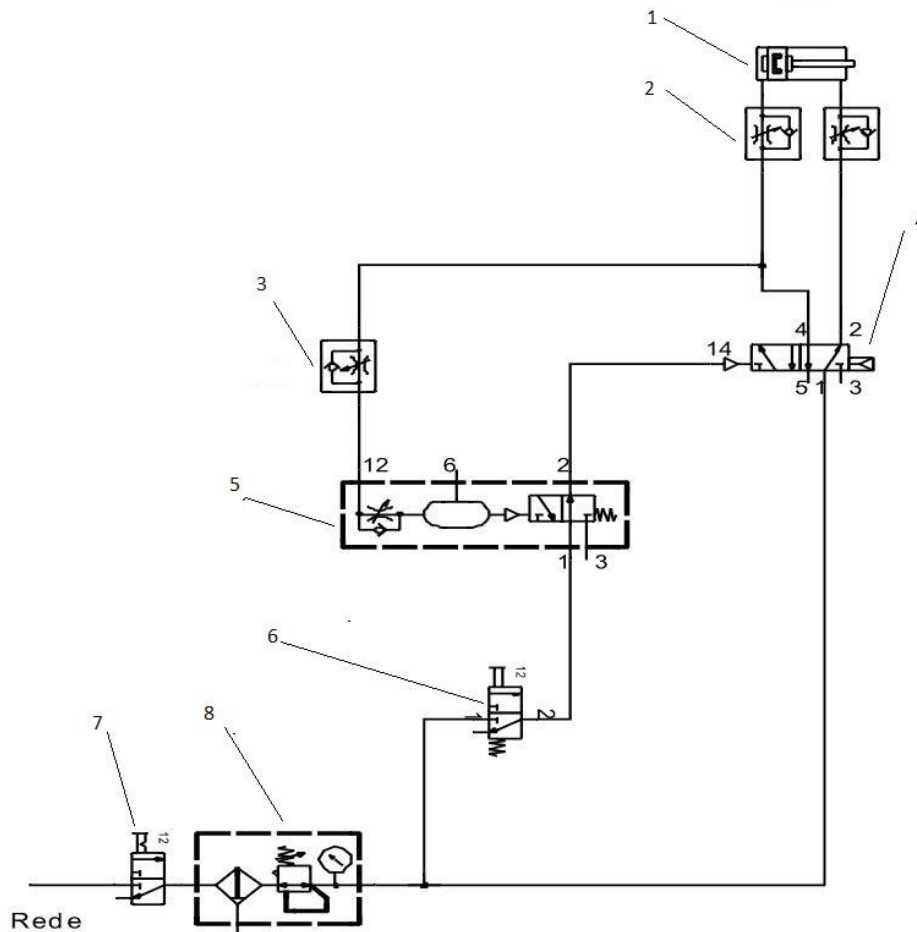


Fig 5.4 Pneumatic system for test station.

Table 5.1 Parts list for pneumatic system of test station.

Nr. on schema	Type of part	Quantity	Catalog number
1	Guide cylinder	1	DFM-12-40-P-A-GF
2	One-way control valve	2	GRLA-M5-QS-4-D
3	One-way flow control valve	1	GR-QS-4
4	Pneumatic valve	1	VUWG-L14-M52-A-G18
5	Time delay valve	1	SV-3-M5 / VZO-3-PK-3
6	Front panel valve / Selector switch	1	N-22-SW
7	On-off valve	1	HE-D-MINI
8	Filter regulator	1	LFR-1/4-D-MINI

5.4 Gluing connectors to cups

This section was added to this subchapter because it is too short and not significant enough for a whole separated chapter. After welding all parts of a cup, and testing a connector, one part of it must be glued to the base of a cup. Except a longer time of binding it requires a proper force to make sure that the layer of glue is as thin as possible, end that bonded elements are in proper position. There was a need to create a special table which will allow the operator to make his task quickly, with a group of at least 10 cups, fast and secure assembling cups and plastic parts in holes, and easy way to free bonded elements. Primary idea said that each cup will be fixed to the table with a group of 8 pins, inserted to a table on one side and reducing degrees of freedom of a cup. From the top parts should be secured with Speedyblocks. Fig 5.5 shows a view of

primary concept. The part (2) that presses the glued connector (3) to cup (4) is mounted on an arm of Speedyblock (1). Cup is secured on the table (5) with group of 8 pins (6). However, the whole station length is over 2400 mm. Aluminum plates of that size are very hard to machine and relatively expensive.

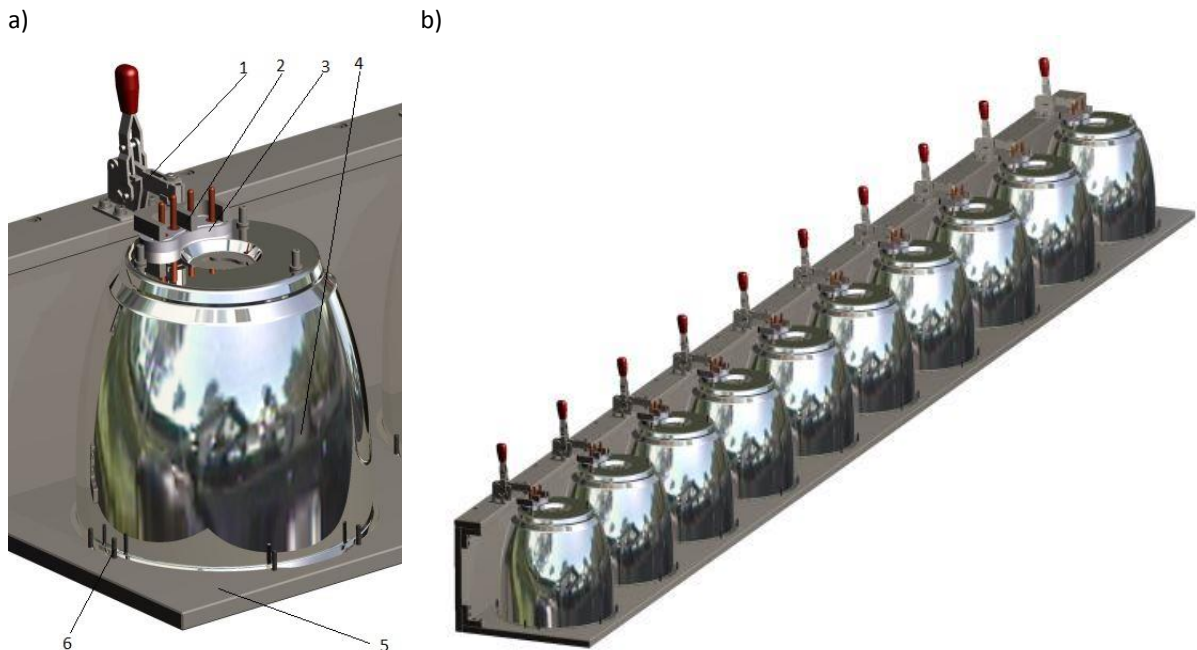


Fig 5.5 Primary version of gluing station: a) single cup view, b) view of the whole station.

The constructor change this concept and decided to make a welded frame from steel profiles 30 mm x 30 mm x 1.5 mm; ISO 4019-1982. This type of component manufacturing is much cheaper and suitable for construction working under relatively low forces. Instead of making single, long construction, it was replaced with 2x5 rows of cups. Big metal plate was changed by MDF. This is a type of wooden composite, which contains cellulosic fibers, joined together under pressure and heat with use of synthetic resin or other bonding synthetic adhesive. Its density is usually between 500 and 850 kg/m³. This material is good for machining, but not resistive for humidity or contact with oil (it absorbs liquids) [XVIII][18]. A special shape for cups was milled in those plates to enable a cup to move. Final 3D model of the station was presented on Fig 5.6.

5.5 Summary

The test station has simple construction, it is easy to mount a new pair of connectors in time shorter than one minute. Thanks to the pneumatic system, containing a timer it was possible to avoid any extra programmable controllers. By switching just two buttons operator can immediately start tests. The gluing station, thanks to use of steel profiles possess quite light and cheap construction, easy for manufacturing. Change of idea helped to save expenses, save space and material.



Fig 5.6 Final version of gluing station.

6. Screwing station

6.1 Issue description

The kitchen robot has a housing containing two main parts (top and bottom part). These plastic forms are multifunctional: they support mechanical and electronical parts, define shape of the robot, isolate and protect from external environment. The two parts are fixed with 6 screws, which go deep inside the housing forms. Fig 6.1 presents both of main parts of housing in exploded view; black circles are the places in bottom part where heads of screws have their default location. As it can be noticed, the screws must be applied from the bottom of housing.



Fig 6.1 Main parts of robot housing.

The problem, that needed to be solved is to make single-person station for assembling those parts when all components of the robot are already inside. Main difficulties according to this issue were as follows:

- screws applied from the bottom side of the robot, which means that the robot must be reversed upside down during process or the orientation of screws must be upside down (heads down, tips up) during mounting;
- hard access to the nests of screws;
- nests are not coplanar, different height of columns and different shape;
- screwing not possible without some fixing of housings; both hands are needed to hold the robot in proper alignment;
- screwing is one chain in assembly line, what means that this operation cannot last longer than 60 seconds which is the cycle time;
- station must be fully adjusted to the construction of assembly line, space limits, position of conveyer, table size, etc.
- operating at the station must be simple enough to not require extra personal training.

6.1.1 Assembly line

Before the beginning of design process there was a need to exam assembly line, its way of work and limits. Fig 6.2 presents assembly line of the kitchen robot.

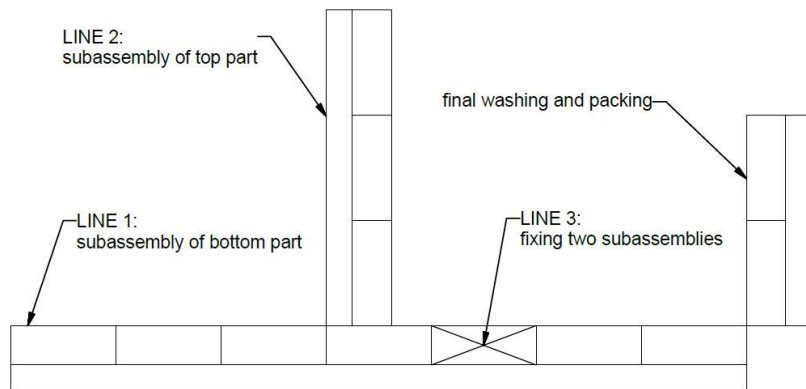


Fig 6.2 Assembly line sketch.

Line 1 contains a group of stations where operations related to mounting all parts to the bottom housing are made. An operator makes a single operation and puts the assembled parts on conveyer; for example on one station a motor is fixed to the bottom of housing. Perpendicularly to *Line 1* runs *Line 2*, where all assembly operations about upper parts are being made, including fixing the display and electronic hardware. In the place where two lines meet each other the screwing station must be located. When both subassemblies are together it is time to add turning on/off button before final washing and packing. Presently, the movement of products along the lines is made manually, but in the nearest future belt conveyors driven by electric motors will be applied.

A single station (Fig 6.3) contains a table, 540 mm depth and 940 mm width, with adjustable angle of slope and frame to which a lightning is mounted. The top profiles of the frame are 1150 mm above the table. There is a conveyer in front of station, 355 mm width. To compare, the size of top housing part is 380 x 200 x 230 mm³, bottom part has dimensions 380 x 200 x 80 mm³, and fixed together they have height of 263 mm. The sizes of fixing screw is M2.5x20.

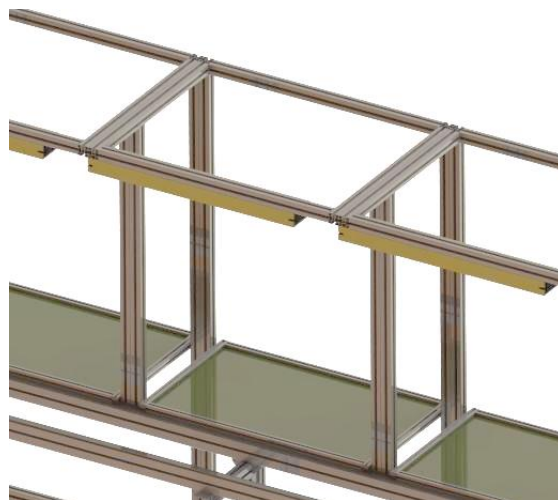


Fig 6.3 View of a single station in the assembly line.

6.2 Solution proposals

The first thing worth to discuss was: if the station should be fully automated, half-automated or completely operated by a man.

6.2.1 Partially automatic system

It begun with a concept of partially automatic system, with using 3-DOF (Degrees of Freedom) kinematic structure, for example 3 translation kinematic pairs moving in perpendicular axes, combined in structure of gantry manipulator (Fig 6.4 a)). This machine can have a screw driver, mounted on the last part. This tool, with magnetic head could pick up screws from a storage-matrix, place it in proper position, and screw. Alternative solution is to use a system with 2 rotational and 1 translational pair, all parallel axes – SCARA (Fig 6.4 b)).

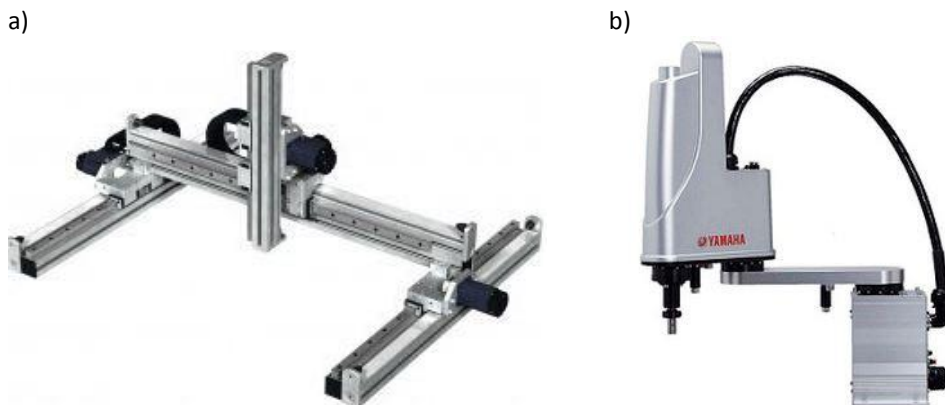


Fig 6.4 a) Structure of typical 3-DOF gantry manipulator [XIX], b) structure of typical 3-DOF SCARA manipulator [XX].

However this solution still does not solve a problem of aligning parts of housing and requires putting the housing in proper position, which means a need of operator presence.

6.2.2 Fully automatic system

All problems can be solved, if the operator from previous station (the one before screwing station) could put both parts in a special form where the housing is reversed upside down. Furthermore, this package is put on the conveyor, which brings this part in a proper position, the rest of process is done as described above. In the end, conveyor brings the assembly to the next station and a new pair of housing parts is coming to the screwing station.

6.2.3 Single operator station

All disadvantages of automatic station must be taken into account. First of all: buying an industrial robot is related to high expenses. What is more, in case of integration with conveyor, external control system is required, including sensors for housing detection, which brings extra costs. In case of some failures, the whole assembly line must be stopped. There is also a need of periodical control of equipment. That is why during brainstorm the team decided that it is better

to design easy to use, manual station, with no sensors, nor actuators. All disadvantages and advantages of the three concepts were described in Table 6.1.

Table 6.1 Comparing advantages and disadvantages of stations.

Category	Half automatic station	Fully automatic station	Single operator station
Costs of production (scale 0...10)	8	10	1
Time of preparing (scale 0...10)	7	10	2-3
Operator costs (scale 0...1)	1	0	1
Need of servicing	Yes	Yes	No
Risk of failure	Quite big	Big	No risk
Labor of an operator	Average	No labor	Big

Taking into account all of those conditions the team decided to make something which require only single person manual work and no automatics. The completed solution is described in next subchapter.

6.3 Manually operating station

6.3.1 Description of forms for housings

Three main operations that need to be done in this station are: aligning both parts of housing, reversing them upside down and applying screws. The difficulty with screwing is that screws supposed to be put in irregular pattern of holes with small diameter, which is difficult to do quickly. It was decided that parts of housing must be put in some forms, which align them together, making a solid assembly, having the shape of an cuboid. The form for the bottom part should have a group of holes, which allows the operator to put screws quickly in right places and mount them with a screw driver having a bit, which is long enough to reach the bottom of every single hole. To unable the whole pack displacing, what could be uncomfortable for operator, a special cradle was designed.

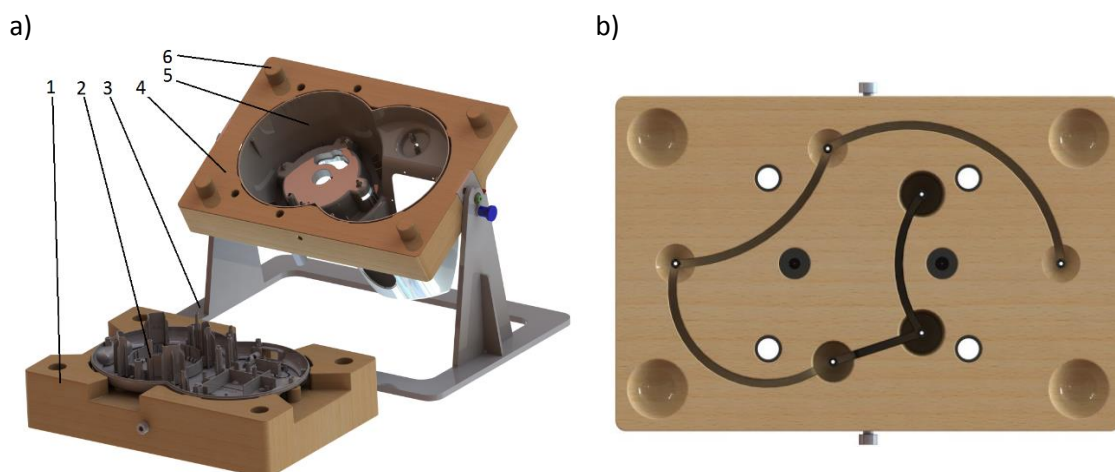


Fig 6.5 a) View of conceptual model of screwing station, b) bottom view of the holes in bottom form.

On Fig 6.5 a) the primary version of station is shown. Each housing part (2,5) has a well suited MDF form (1,4). For better alignment a 4-pins rectangular pattern in top form was used, so the top form can go easily to the bottom form. On Fig 6.5 b) 6-holes pattern was shown. Holes are

connected with a path, which a screw driver should follow. The shape of holes allows an operator to put the screws not very precisely (they geometry makes the screws will reach the holes of housing perfectly). It was done this way, that the beginning of the route is in the whole on the right side and then the bit of the driver goes to holes being suited deeper into the housing. A section view (Fig 6.6) going thru the form shows how the screw driver inserts the hole. It is easy to see that the hole have slopes to avoid dynamic falling and risk of damaging the station.

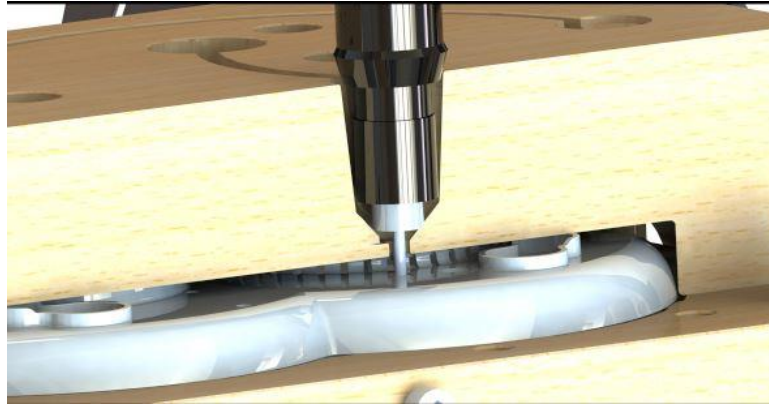


Fig 6.6 Section view of bottom form and screw driver.

This solution solves most of problems, but has two relevant disadvantages:

- operator must pick up the bottom form - from the conveyor to the table and after screwing - back again;
- during aligning forms operator must pick up the bottom form with one hand and secure the top part of housing to not fall from its form with another hand, what is very uncomfortable.

The upgrade of this solution was made, deleting problems mentioned above. Rotational move of the top form was changed into 1-DOF move along the defined path (Fig 6.7).

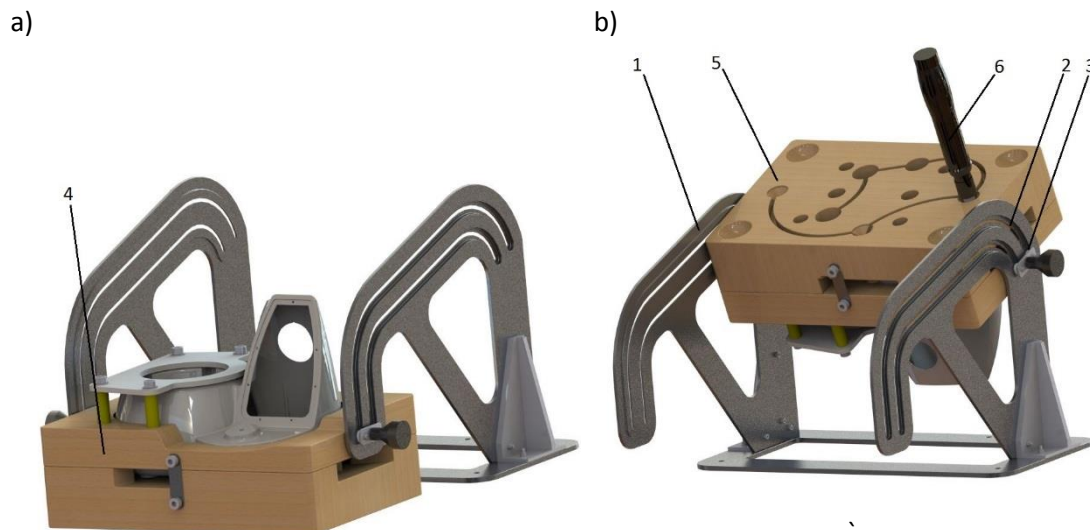


Fig 6.7 Screwing station after upgrade.

Aluminum construction has a pair of long arms (1) containing two pairs of tracks (2), on which a couple of rollers (3) can move. Normally the top form (4) is fixed to the rollers as integrated part of the station. All geometry is defined to allow the top form go along the track and meet a bottom form (5) brought by conveyor (bottom face of frame and bottom form in extreme

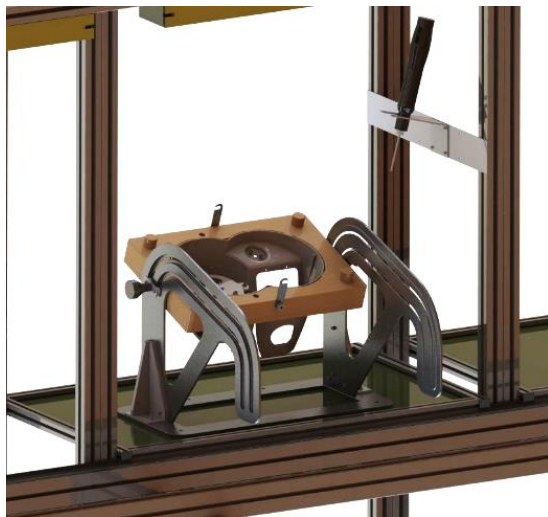
position are coplanar). Next, both forms are fixed together with a hook, operator turns the assembly upside down (normally the bottom face of the form is orientated 30° to vertical, but due to adjustable angle of the table it can be between 0° to 60° in second extreme position). After applying screws, an operator uses the screw driver (6) to insert them.

6.3.2 Algorithm of work

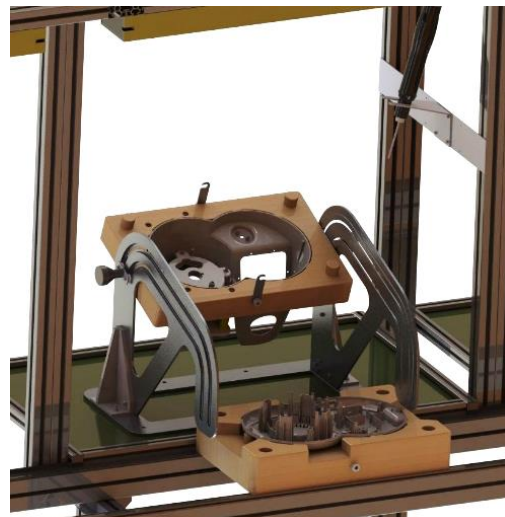
For better understanding how the station should be properly used, in following subchapter an algorithm of work was explained. All steps are shown on the Fig 6.8 a-e:

- a): a new upper housing is put into upper form, which (form) is in up-extreme position; the screw driver is in its default place;
- b): a new bottom housing in a bottom form is brought by the conveyor;
- c): both forms are fixed together with pair of hooks;
- d): assembly is pushed by the operator into up, extreme position; screws are taken from a screw-belt and put into holes; the screw driver is leaded along the path and screws;
- e) after screwing both parts of housing are fixed together and ready for final processes go further in bottom form with conveyer (after 10 cycles a group of bottom forms goes to the beginning of the line).

a)



b)

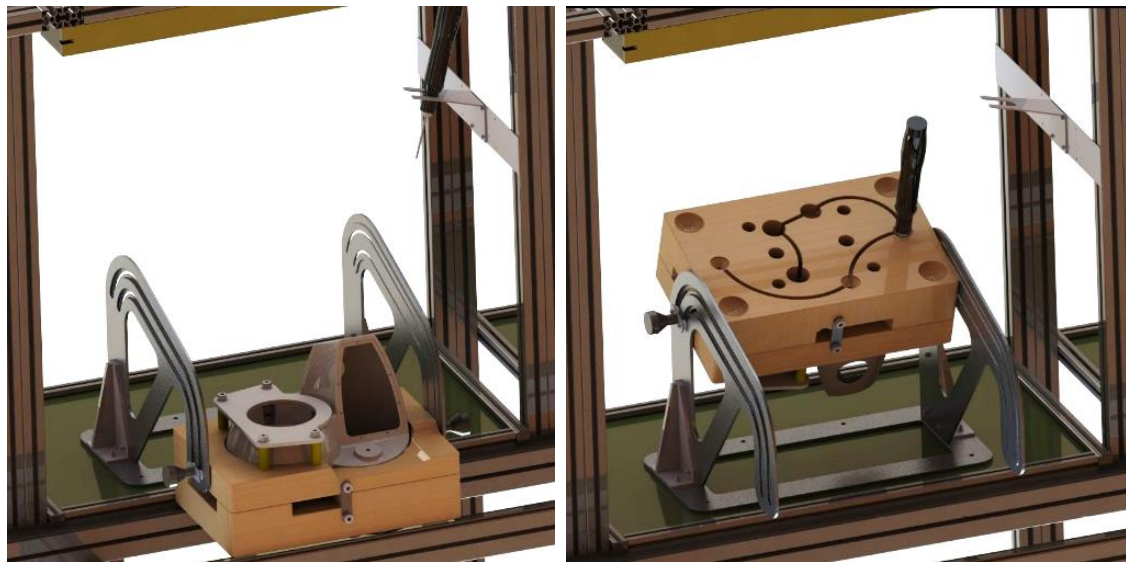


c)



d)





e)



Fig 6.8 Algorithm of work at the station.

6.3.3 Summary

Due to applying an untypical solution, based on simple kinematic structure it was possible to solve the problem of uncomfortable screwing process without use of expensive automatics and spending days on implementation of complicated system. The station is very cheap, contains only 18 parts (except standard parts) which can be made easily on conventional machines or with application of CNC (for forms and frame arms). The structure was designed ergonomically – operator (no matter how tall) will be able to make the whole process standing, without bending his back, due to adjusted angle of slope of the table and quite small space of manual operations (50x60x35 cm³). What is more the station can be adjusted to physical needs of any operator, does not require special, long training before beginning of work and offers comfortable work position.

Part II:

Bowden cables cutting and thermal forming

BACKGROUND

Mechanical cables

Cutting methods and machines

Blades and knives

Thermal forming of small size structures

Summary

7. Background

7.1 Mechanical cables

There are many applications where mechanical cables stand a good solution in the matter of transmitting mechanical energy in required distance. Some of them can be found in daily life, for example in bicycles (brakes and gear shifts) and cars (throttle, cruise control, emergency brakes) [19]. Most of these cables are called *Bowden cables*, which contain a metallic (usually steel) cord moving inside elastic tube [20]. These elements have construction presented on Fig 7.1.



Fig 7.1 Exploded view of Bowden cable [XXI].

Looking from right to left: cable is covered by plastic tube, first inside layer is steel wire spirally encircling the structure, that increases strength parameters. The second inside layer is an inner sleeve, which reduces the drag (all three parts are fixed together). The last part, movable, is a steel cord, usually in shape of twisted wires. To increase durability of these parts lubrication between housings and cords is applied. Types of Bowden cables can be classified in several categories [XXIII], where different properties are taken into account, for example:

- cord construction: 1x7, 1x19, 7x7... (first number is the amount of bunches of wires, and the second is the amount of wires per strand);
- material of cord: stainless steel, galvanized steel, Inconel...
- ends: nipples, ball joints, abutments...

SCS, the client of *PR Metal* produces different types of mechanical cables for automotive and machine industry, sanitary technologies and daily life [XXII]. The company produces also Bowden cables of increased strength (anti-burglar) for car door, applied in some of German automotive brands. The conduit of those cables combines three components: inertial plastic rod, bunch of 18 collinearly situated steel cords, with diameter $\Phi 0.5$, and external cover (Fig 7.2).

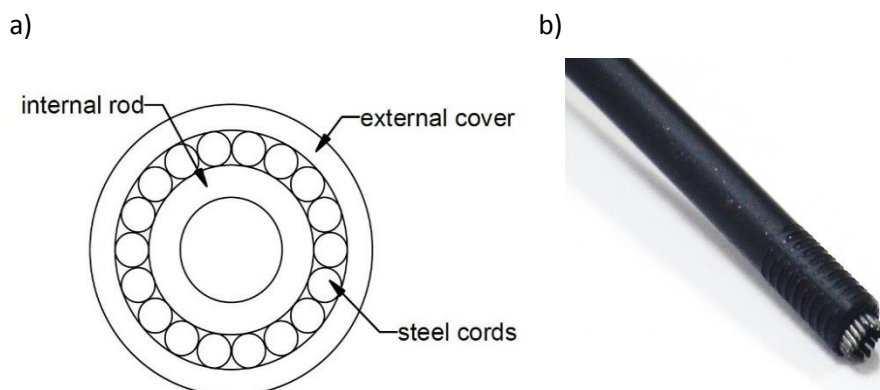


Fig 7.2 Conduit of Bowden cable by SCS: a) section view, b) picture of real part

The process of making these conduits must include final cutting (for required length) and making special grooves for applying ending parts (Fig 7.2 b)). According to information delivered by client present version of the cutting and marking system does not work properly, that is why SCS, ordered the machine which must make both of these operations.

7.2 Cutting methods and machines.

Since the end of previous century, a lot of different methods of cutting materials were invented. In 1989 the team of Japanese scientists and engineers patented water jets for cutting metallic materials, plastics and composites [21]. The concept of this invention is based on using high pressure water stream and abrasive particles (size up to 100 μm) from two different supply sources. The jet is directed on the surface of cut element (Fig 7.3 a)).

Even earlier, first ideas about using focused high power laser beam to cut materials were born [22]. A laser generator produces beam, which runs through optical system containing lenses and mirrors (Fig 7.3 b)). Finally focused beam reaches the material, which is situated close to the very focus (place of the highest power intensity). In case of cutting metal elements to avoid oxidation of cut areas, protection gases: azote, helium, argon are applied [23].

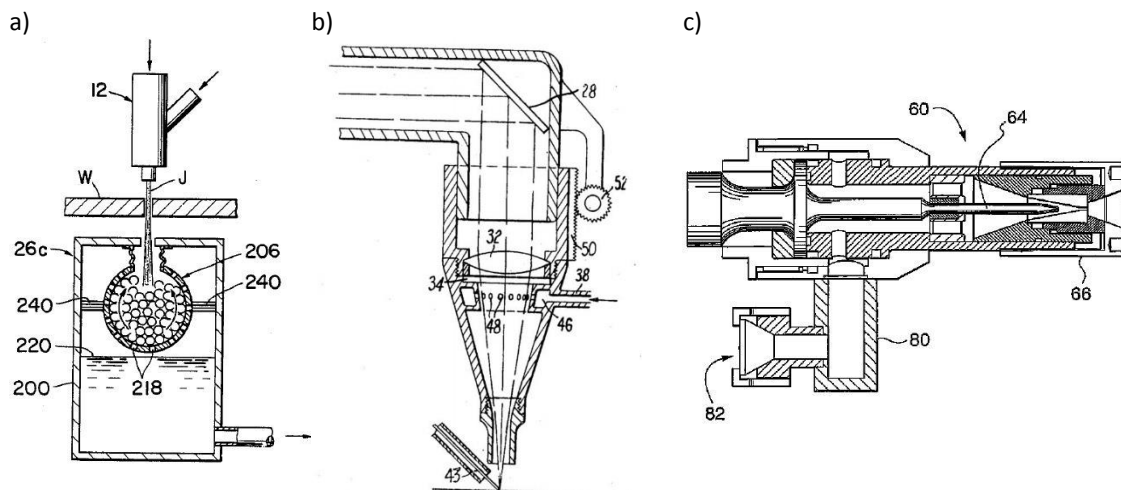


Fig 7.3 a) water jet [21], b) laser cutting [22], c) ultrasonic waterjet [24].

These technologies, and their improvements, e. g. ultrasonic waterjet cutting machine (Fig 7.3 c)) (using high-frequency electric impulses, causing vibrations, to modulate water stream [24]) are sophisticated, very accurate to cut curvy shapes in cooperation with e. g. two-axes table. Unfortunately they have a number of disadvantages that excludes them from our area of interest: all of them require buying relatively expensive equipment. Using them needs accurate hardware and software, extra methods of protection as well. These reasons made us abandon the idea of using one of solutions presented above and focus on classic, mechanical methods of cutting.

Beginning of the research took place from analyzing patented inventions for cable cutting machines. One of these invention disclosure says about automatic cable measuring and cutting machine [25]. Here, a cable is fed through a wheel (driven by motor), containing sensor to gather information about its length. Vertical saw was used as cutting tool, it has caterpillar drive. Its construction also contains a pair of clamps, which can press cut cable to the base during cutting, to prevent undesirable displacement. The sketch of invention was shown on Fig 7.4 a), where saw

wheel and its bearing (109, 110, 112, 113), clamps mechanism (88, 89, 93, 94, 95, 96) and table with fillet for cable support (86) can be found.

Even though the machine which *PR Metal* is going to produce must be fully automatic, some inspirations and ideas can be taken from hand-held devices. The machine described in [26] is powered by compressed air from hand-pump. There are two pairs of jaws in the device: first of them are clamps (9 and 10 on Fig 7.4 b)), which immobilize the wire (71). Second pair (which

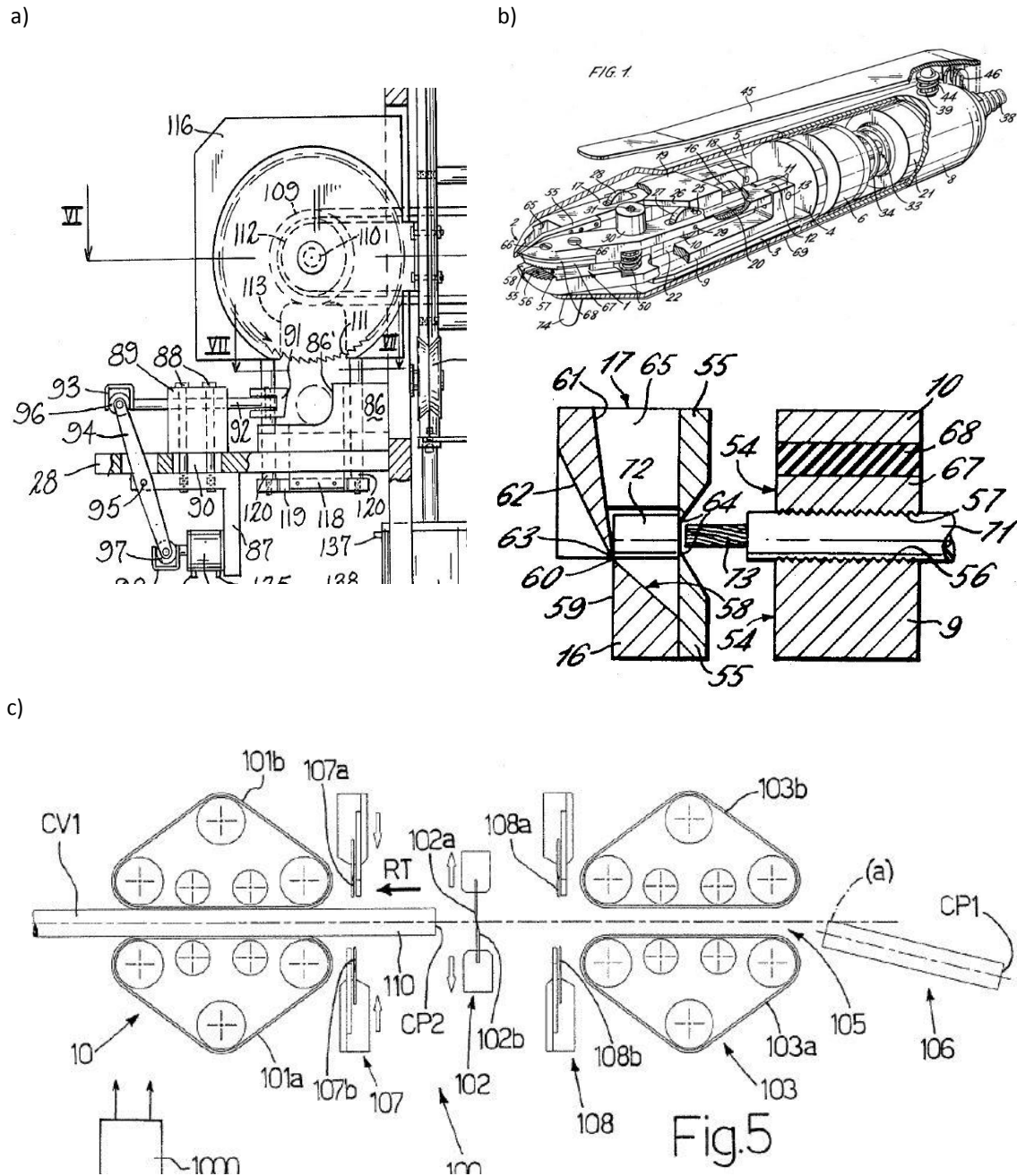


Fig 7.4 a) cable cutting and measuring machine in accordance with [25], b) hand-held device for cutting and stripping cables [26], c) cable cutting and stripping machine [27].

contains all elements on the left side) makes two tasks: stripping the wire (using blades 55) and cutting the cable with use of edges (59, 60, 61, 63). The second pair makes two moves during process. First: it rotates in the axis perpendicular to sketch surface, located above the cable (so its movement is almost linear along the axis of cable). Second: the top jaw moves up and down to cut and strip cable.

Another system for cutting and stripping electric cables [27], was patented by Italian company *Makfil system*. This invention is about the machine for cutting electric cables having a sheath of insulating material (Fig 7.4 c)). It has a head which with one pair of stripping devices (107, 108) and two blades to cut (102). A cable CV1 is fed along AV direction. Simultaneous work of stripping devices allows to reduce worktime twice (to compare with machines previously existing on the market). Work of the machine can be described in several steps. First the stripping a first end (CP2) of said cable (CV1) and cutting said cable (CV1) to form a cable portion and the rest of cable (CV2). Further: feeding remaining cable (CV2) by wanted length, stripping an opposite end (invisible on the drawing) of said cable portion and one end of the remaining cable (invisible on the drawing), simultaneously.

7.3 Blades and knives

All methods of cutting material in conventional way can be divided into two categories: with removing material and without removing material and depending on the movement of tool: rotating tools and tools with translational displacement. Mechanical removing material is in that case done by sawing. Taking into account the specification of cable construction, applying a saw for the conduit, containing elastomer may cause deformation and edges frying, what can deform grooves (that was the main defect in previous version of the machine). That is why the only considered solution was application of knives or shearing blades (which means not removing material).

In industrial applications, for cutting tubes, some round knives are used [XXIV]. These type of devices does not cause big damages in material. One of the most important parameters of round knives is the shape of the blade, which has influence on sharpness but also durability of the knife. These types of tools are used as singles, never in couples.

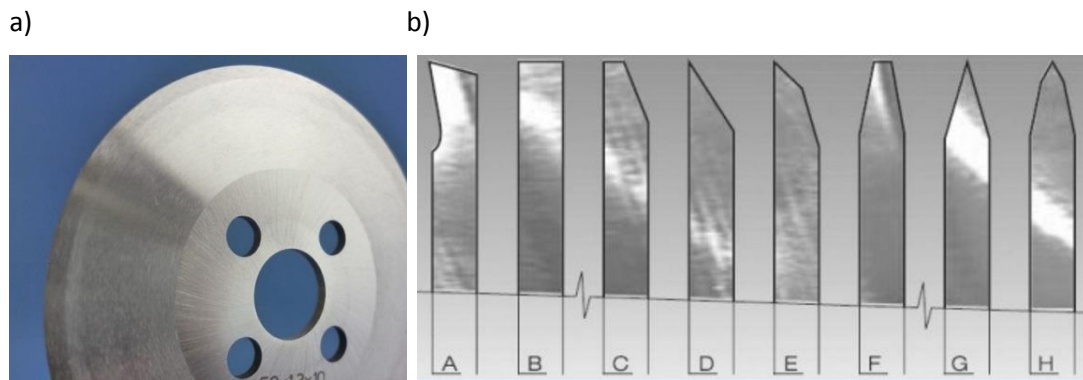


Fig 7.5 Round blades: a) external shape, b) geometry of blades [XXIV].

Another group of cutting tools are these which make translational move during cutting. These group of knives has section geometry similar to round knives, presented above. According to patent [28] these tools can work properly, when the force is put possibly close to flat surface (or surface of symmetry), parallel to it. Suggested way of application is using a cylinder, which supposed to move its piston along the direction of cutting. Examples of those blades were shown on Fig 7.6. It is easy to see that those types of blades are very smooth in all cases. Unsymmetrical blades are more sharper but symmetrical have bigger durability and are more resistive for bending moments [XXV]. What is more these types of blades are used with dies or in couples, to create a force for cutting material.

In industrial applications also another type of cutting devices is used. One of them are band saw blades. They make oscillating or constant movement in direction perpendicular to the direction of cutting. Rectangular blades (without specified cutting edge) usually based on high forces and working in pairs to make strain in direction parallel to the force direction. Main application of these knives is cutting thin metal sheets or plates. Both types of blades are presented on Fig 7.7.

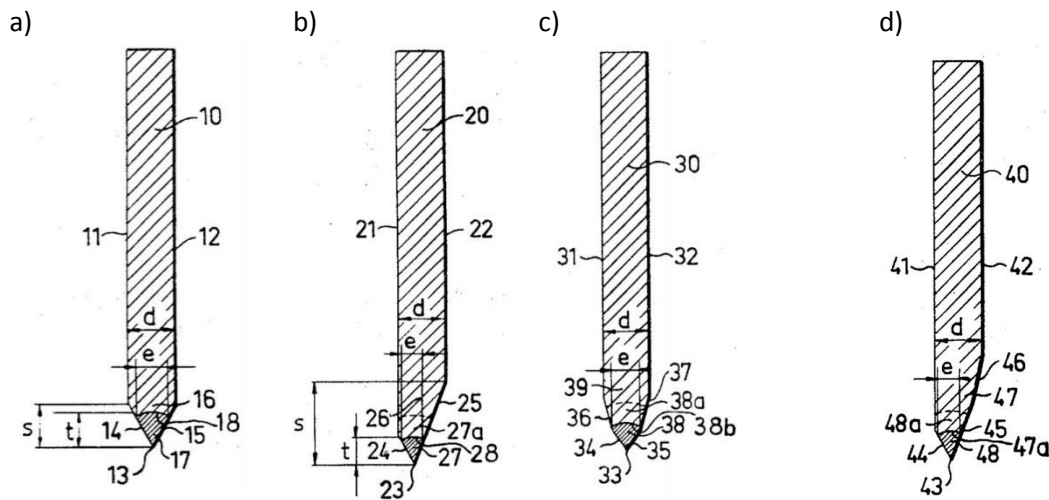


Fig 7.6 Different shapes of cutting blades [28].

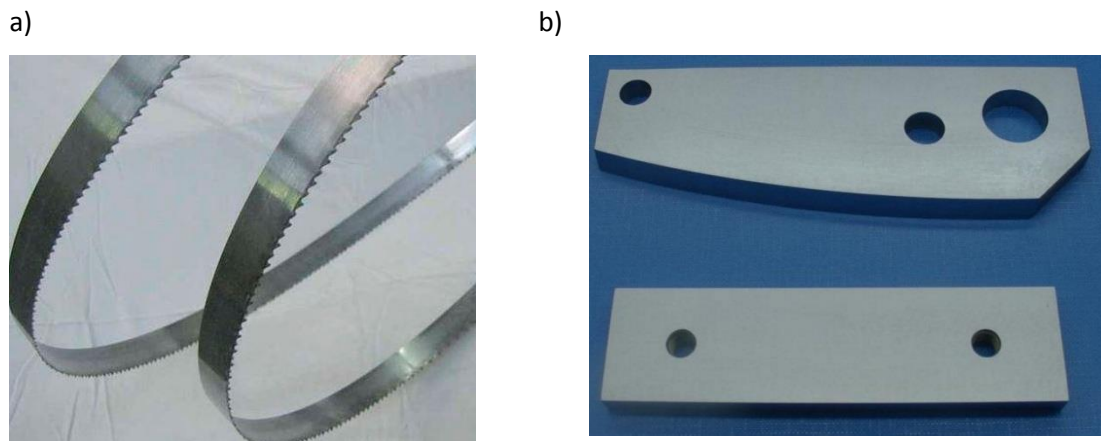


Fig 7.7 a) Band saw blades [XXVI]; b) rectangular blades for metal sheets and plates cutting [XXVII].

7.3.1 Materials

Three main groups of materials can be used for blades production: steel, ceramics and diamond, which is allotropic structure of carbon [XXVIII]. All of them have similar features: high hardness, long durability, wear resistance, very good strength parameters. Diamond blades are usually applicable in milling machines, saws, and machines for final surface manufacturing. They are also used in hard brittle materials manufacturing. The biggest group of blade materials, steel, contains over a dozen types: tool steel, alloy steel, semi-stainless and stainless steel and many others. Good cutting properties, strength and durability are achieved by alloying elements: carbon, molybdenum, chrome, vanadium, cobalt, silicon, manganese, tungsten.

HSS (High-speed steel) is the most often used in the manufacture of various cutting tools. All requirements for classification are enclosed in Fig 7.8. Except proper amount of alloying elements, HSS must have ability to be austenitized, hardness above 63 HRC in normal conditions. There are three groups of HSS: Tungsten (types T1, T5, T15), Molybdenum, having around 63-65 HRC (types M1, M2, M7, M50) and Cobalt, having around 63-65 HRC (types M35, M42). HSS have good properties also due to temperature treatment, which is carried out in several steps: preheating, austenitizing, quenching and at least three: tempers below critical temperature. Cutoff tools, which are the field of our interest are usually made from M2 steel type with TiC-TiN (titanium carbide – titanium nitride) coating.

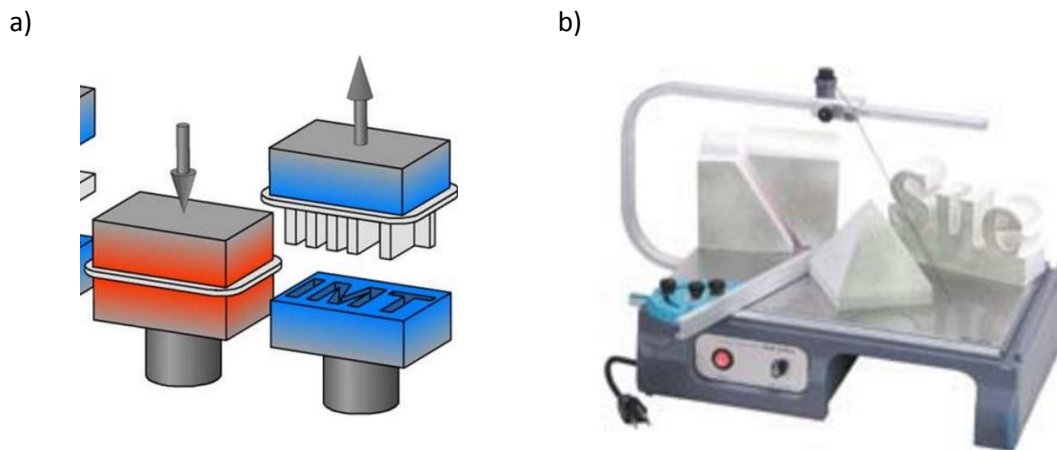


Fig 7.8 Methods of temperature plastics forming: a) hot embossing [XXXI], b) hot wire cutter [XXXII].

Requirement	Standard	Intermediate
Chemical requirements		
Minimum alloy content by major elements		
Carbon	0.65	0.70
Chromium	3.50	3.25
Vanadium	0.80	0.80
Tungsten + 1.8% molybdenum ...	11.75	6.50
Minimum total alloy content based on tungsten equivalents ($\frac{1}{3} Cr + 6.2 V + W + 1.8 Mo$)		
Grades containing less than 5% cobalt		
cobalt	22.50	13.00
Grades containing 5% or more cobalt		
cobalt	21.00	12.00
Hardening response requirements		
Ability to be austenitized, and tempered at a temperature not less than 510 °C (950 °F) with a fine-grain structure (Snyder-Graff grain size 8 min) to		
	63 HRC	62 HRC

Fig 7.8 Table containing minimum requirements that steel must met to be classified as HSS (according to ASTM) [31].

7.4 Thermal forming of small size structures

As it was said at the beginning of this chapter, except cutting conduits, the machine must make grooves in plastic cover. Those grooves have about 0,2 mm width and 0,1 mm depth. The most intuitive way for making shapes of that size in thermoplastic material seems to be a process with use of heat to make material able to forming and stamp having required shape. The cover of cable is made of Polypropylene (PP), which melting point is 139°C – 171°C [XXIX]. The name of thermoforming [32] is reserved for the process of heating plastic sheet or film above the temperature, which allow the material to pliable forming with use of mold, further stretching and cooling, until having designed shape. Plastic cups, plates, bowls are example products of this process.

More accurate process is hot embossing. This forming process allows to make microstructures in thermoplastic polymers, during which the substrate is heated not much above melting point, after that a stempel is pressed on polymer surface. The part is cooled down and the polymer is removed [XXX] (**Błąd! Nie można odnaleźć źródła odwołania. a)**). Another, simpler method of forming plastic parts is hot wire cutter. A wire string is heated over melting point of material that needs to be cut. With adjusted speed, the plastic part moves along required path and is cut by hot wire. This simple device is good for straight-wall parts (**Błąd! Nie można odnaleźć źródła odwołania. b)**).

7.5 Summary

This section contains multi-faced description of the case. Bowden cables: its construction, material characteristics and application were mentioned on the beginning. Machine functionality and processes requirements were described. Further, many methods of cutting, starting with new technologies: high pressure waterjet, laser and ultra-waves, next: conventional methods. Some of them, which were considered as useless in our case or too expensive were eliminated. Further all industrial types of cutting tools, its way of work, basic geometry, shapes, advantages and disadvantages were listed. Attention were also focused on their materials, especially high-speed steel, which is widely used. At the end, methods and devices, which should be considered as helpful in making grooves were described. All this analysis will be very useful during first part of project, selecting best ideas and project development.

DEVELOPMENT

Problem Analysis

Brainstorming, preliminary drafts and solution selection

Developing the main idea

Budgeting

Critical Analysis and Prospects of Development

Equipment Instruction Manual

Maintenance Guidelines

8. Development

8.1 Problem analysis

Analyzing the case of cutting machine there was a need to be focused on two basic questions: what precisely is required and what are our possibilities and limits. The whole project was made with attention paid to manufacturing technology available in the company and its equipment. Main things that were considered and solved during machine design are listed below:

- creating general concept of machine;
- combining two processes into single one;
- customer requirements e. g. quick access to blades, small space consumption, production hall conditions, costs.
- analysis of forces required to cut the cable;
- actuators and whole standard equipment selection;
- cutting blades shape, dimensions and material selection;
- providing heat, temperature control, insulation;
- manufacturing, dimensions control, chain of tolerances;
- parts (particularly blades) positioning;

It must be known that experts working in *PR* company have noteworthy experience with this type of cables manufacturing, including cutting conduits. That is why some simulations, steps and analysis were not done, also because a short period of time was predicted for the project.

8.2 Brainstorming, preliminary drafts, selection of solution.

The heart of problem had three points which required consideration:

- how to combine cutting and thermal forming;
- what way of cutting tool use and how to generate force required to do it;
- how to avoid destroying markings during cutting.

There was a couple of ideas which lead the team to final solution. First was sketched and presented on Fig 8.1.

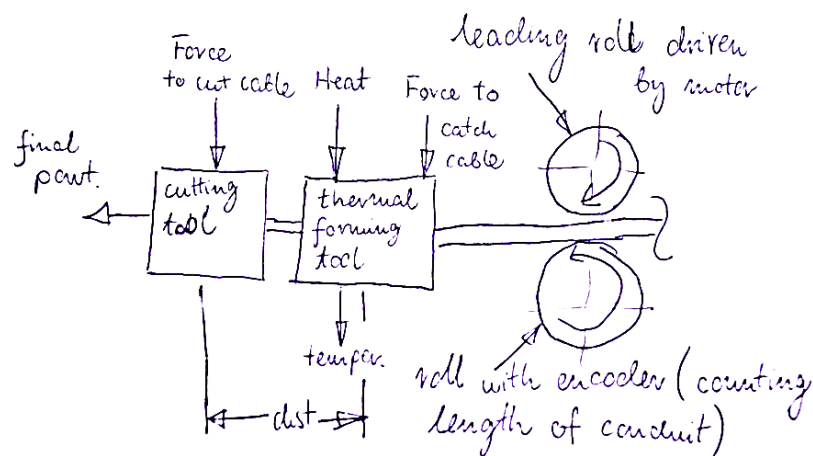


Fig 8.1 Conceptual sketch of the machine (1).

In that case processes remain separated. There is a pair of rollers used for guiding the conduit and measuring the length. Conduit is stopped twice: first time to allow the forming device to make grooves and second time for cutting. It could be also modified by adjusting the distance between those tools to length of the conduit to stop it just once, for cutting of 1st conduit and forming one end of 1st and 2nd conduit ends. However taking into account length of cable it is unnecessary increasing size of the machine.

Another solution presented on Fig 8.2 reverses order of the processes: first: cutting and later: forming. In that case to guide the part of a conduit that is cut off, second pair of rollers is needed. There is no need to stop the conduit before cutting, only during thermal forming.

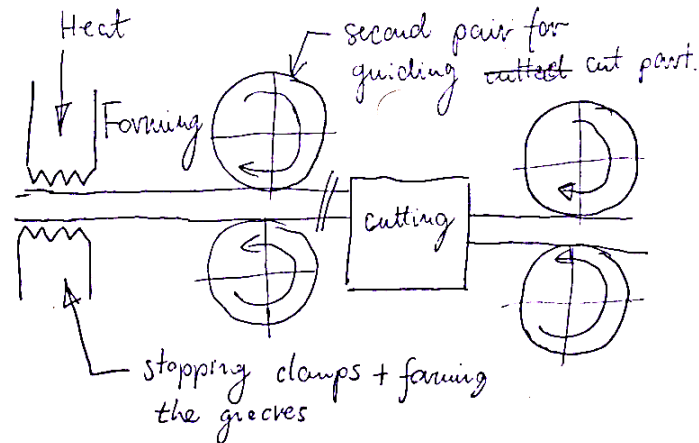


Fig 8.2 Conceptual sketch of the machine (2).

Final concept (Fig 8.3) was based on two of previous and solution described in patents from background section (shown on Fig 7.4 b) and c)). To avoid unnecessary stopping the rollers forming tools were placed on both sides of cutting tool and combined into single sequence of movements. Because the roller works with constant speed, a conduit will buckle due to its elasticity. The energy accumulated in conduit will be used for further pushing the cut of part (conduit is guided in a tube on both sides of tooling).

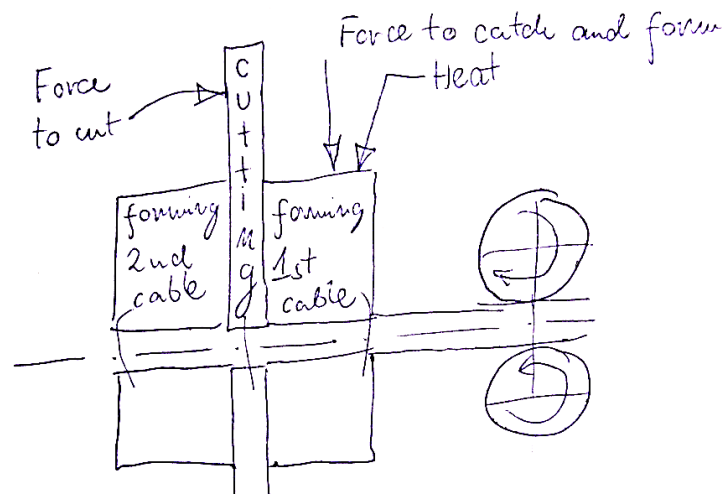


Fig 8.3 Conceptual sketch of the machine (3).

The way of cutting the conduit and blade selection was made after a brainstorm and consulting possible solutions. Rotating tool – a shield knife used to be apply for similar solution. However, due to plastic components such as cover and internal tube, this idea was denied. Materials like

PE and PP has low melting point (about 115 – 150 °C) which may cause some damages of ends of a conduit being in contact with high temperature. Burning or deforming of those parts is very unpleasant even in small range. That is why the only remaining solution is a blade with die or pair of blades. Using two blades with one common cutting surface causes bending and stretching of plastic parts. Application of blade with some die is good with more brittle materials, but in our case it might cause not fully cut of such elastic parts. The best solution seems to be application of a pair of symmetrical blades. Due to big forces appearing in the process, instead of sharpness more important seems to be strength and durable. That is why proposed shape of the blade is the one shown on Fig 7.6 c). According to experts knowledge this blade, applied in another machine makes its work irreproachable.

8.3 Final solutions development and detailed description

This chapter stands a detailed description of final version of the machine. Drawings of all the parts, assemblies and sketches were taken from last revision of 3D model and 2D documentation.

8.3.1 Machine overview

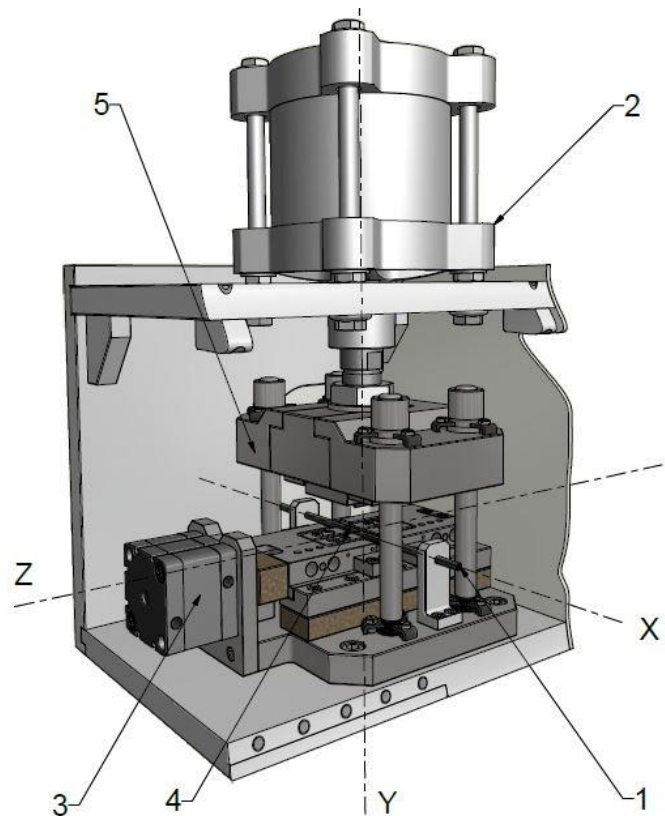


Fig 8.4 Machine overview.

All operations done on the machine are associated to three main, perpendicular axes: X, Y, Z (Fig 8.4). X-axis is the one along which the conduit (1) goes. The conduit is pushed with a system (not included on the drawing), which also measures the length of conduit that runs through it. For making the force that is required for cutting a conduit, a pneumatic cylinder (2) was applied, which moves the top blade system (5) along Y-axis. Another system, responsible for thermoforming catches the conduit with clamps (4) which move along Z-axis, driven by second cylinder (3).

8.3.2 Processes description

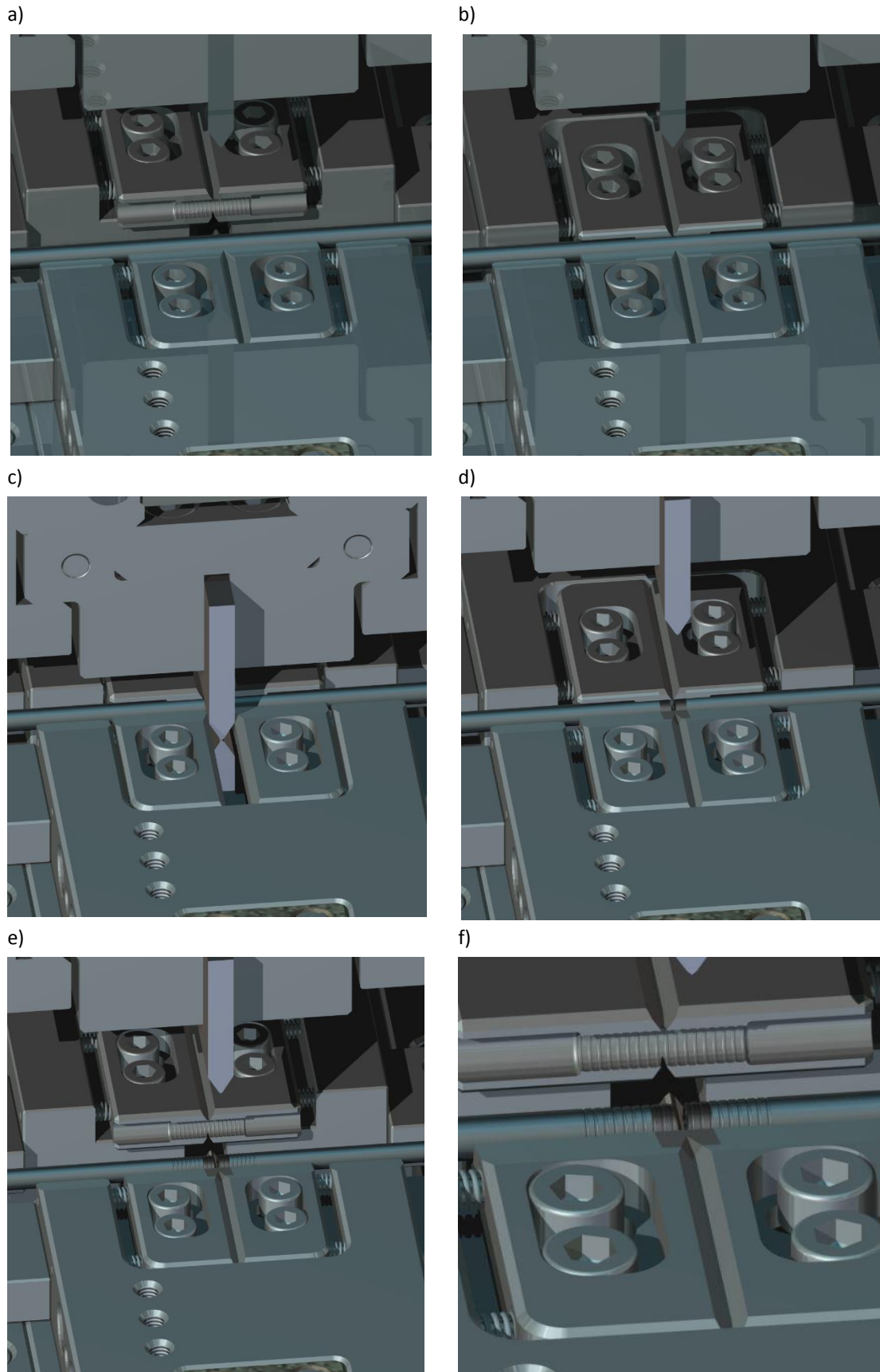


Fig 8.5 Thermoforming and cutting process shown in steps (explanation of each step is provided in the text below).

The processes of cutting and thermal forming conduits were united and designed as one simultaneous sequence of both cylinders and groups of parts movement. All steps were shown on Fig 8.5 a)-f). Construction of mechanisms and parts is described further. Fig 8.5 a) presents situation where the clamps are open and the conduit can move easily. When the control system calculates needed length to cut, the clamps close the conduit (Fig 8.5 b)). Both pairs of hot clamps have ribs, that form the cover. Further, the top blade goes down, cutting the conduit; the same blade pushes clamps in both sides (Fig 8.5 c)) which still hold the cover. The cover is squeezed along its axis. In next steps the top blade goes up (Fig 8.5 d)) and clamps return to the initial position (Fig 8.5 e)). On Fig 8.5 f) grooves, being the result of thermoforming were presented.

8.3.3 Cylinder for cutting system

According to the trials carried out by the client, the force required to cut the conduit, taking into account safety coefficient is equal to $P_c = 6,0 \div 8,5 \text{ kN}$. For this needs a linear pneumatic cylinder should be applied, for the same reasons as it was applied in previous projects: easy access to compressed to 6 bars air and simple introduction to the system. The required diameter of the cylinder is calculated (8.2):

$$D = \sqrt{\frac{4P_c}{\pi p}} = \sqrt{\frac{4 * 8500}{3,14 * 0,6 * 10^6}} = 0,134 \text{ m} = 134 \text{ mm} \quad (8.1)$$

In accordance with ISO 15552 standard, the first appropriate diameter is 160 mm. Festo cylinder, DSBG-160-25 was chosen. It can generate static force of over 12 kN, advancing [34].

8.3.4 Press guidelines

In each translational moving mechanical system guidelines application has two goals: defining and stabilizing way line of move and taking forces and momentums, loading the construction. In case of these project the force needed to cut conduits works (in theory) along Y-axis (see Fig 8.6), which does not make any other force except axial force along the piston rod.

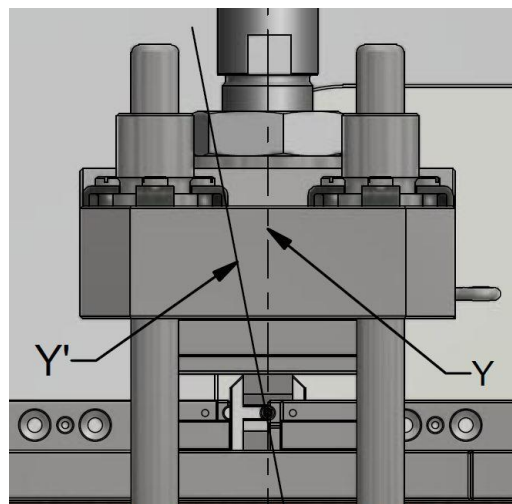


Fig 8.6 Direction of cutting forces.

Anyway because of heterogeneous structure of conduit, some geometrical and shape deviations in manufactured parts and wear of blades, the force can load the construction and piston with some momentums. To avoid that, constructor decided to apply one (in primary version) and

further two pairs of guidelines (columns) to this construction. In that case the only criteria of selection were: easy application and montage, and price. A complete of columns (*ECO 4*) with round sliding bearing (*EBU7-19-Medium*), made by Portuguese *Coferac* company were chosen (see Fig 8.7).

a)



b)

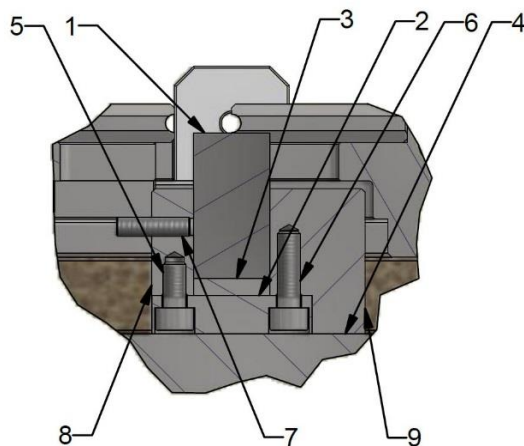


Fig 8.7 a) Linear sliding bushings , b) Linear guidelines (columns) by *Coferac* [XXXIII].

8.3.5 Blades

It was already said that as cutting tool a pair of bevel blades, made of HSS M2 steel was chosen (Fig 7.6 b)). Anyway, in case of failure during test phase, the tooling can be very quickly changed and a pair of unsymmetrical blades (with one common surface) can be applied. On (Fig 8.8 a)) the way of fixing blade is shown. The blade (1) is surrounded and fixed between four walls of parts 8 and 9. Part 2 takes all the load forces during cutting. To adjust the proper position of cutting edge, part 3 (shim pack) has been applied. Parts 2, 8, 9 are screwed together with 5, 6 and another screws, whose are invisible on the drawing. Loose fitting was used in this solution, but to secure the blade against small displacements a screw (7) was used. Fig 8.8 b) presents dimensions of both of blades (they are the same).

a)



b)

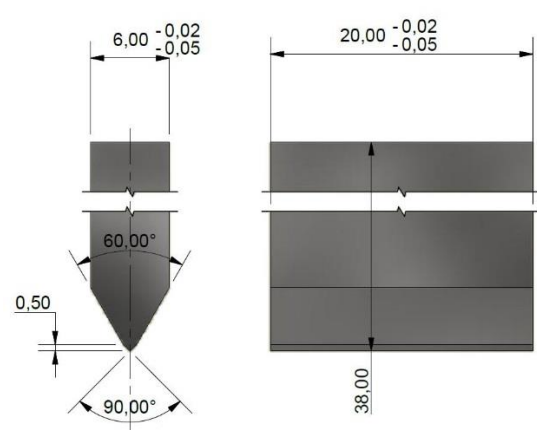


Fig 8.8 a) Blade montage, b) Linear guidelines by *Coferac* [XXXIII].

8.3.6 Heating, temperature measuring, isolation

As mentioned in background chapter, for forming grooves the material must be heated to temperature below polypropylene melting point (around 120 °C). Precise value will be selected after first tests. To heat, both pairs of clamps (made of steel) are mechanically connected to

sleighs into which two resistances are put (5, 7 on Fig 8.9). There is also a need of feedback (temperature measuring) for building closed-loop transfer function. For this purpose each sleigh has a thermocouple for measuring the temperature. They will be inserted in middle holes (6).

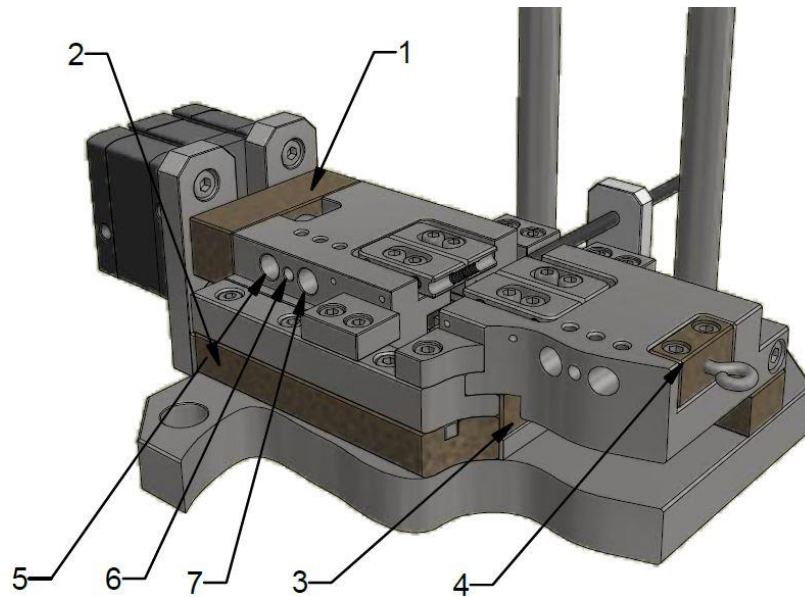


Fig 8.9 Heating, temperature measuring and isolation system in press table.

Cartridge heaters have dimensions $\phi 12 \times 60$ mm and maximum output power 700 W (each of them). Thermocouples are J-type: iron-constantan (Cu-Ni alloy) with measuring range from -40 °C to 700 °C, and high sensitivity: $50 \mu\text{V}/^\circ\text{C}$ (both products by *Resisterma* company) [XXXIV]. Cartridge heaters, thermocouples and celeron shown on Fig 8.10. a), b). To protect the rest of machine against adverse temperature influence, insulation blocks were applied, each number points another insulation to protect: 1 - cylinder, 2 - base plate, 3 – bottom blade, 4 – montage hook handle. Material which was selected for insulation is Celeron (this material is often used by *PR Metal* projects). The composite is constituted of fiber reinforced laminated plastic with good temperature and electrical resistance and mechanical strength [XXXVI].

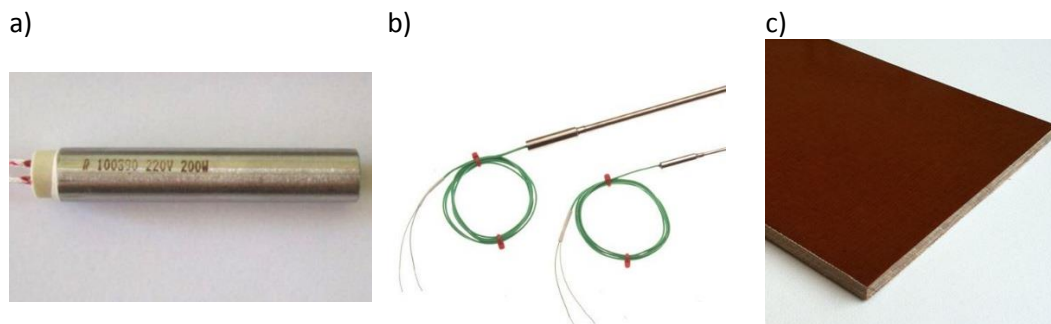


Fig 8.10 a) cartridge heaters b) thermocouples [XXXVI] c) celeron [XXXV].

8.3.7 Conduit holding system

This system was created to carry out two tasks: immobilize conduits during cutting and to make grooves. The conduit is lead through a stiff, plastic tube (6, Fig 8.11), which is inserted into the hole in aluminum part (8). To catch a conduit during cutting two pairs of clamps (4) were used. They have a special spring system, which will be described in next subchapter. Clamps are fixed to a pair of sleighs: 3 – unmovable, 2 – movable, sliding on trails (6). Movement of 2 is achieved due to pneumatic cylinder 1 (AND-63-15-I-P-A, with 15 mm stroke [36]). Selection of the cylinder

was done basing on company's resources (no significant forces appear). For securing the move of sleigh 2, and position of sleigh 3, four plates (5) were applied.

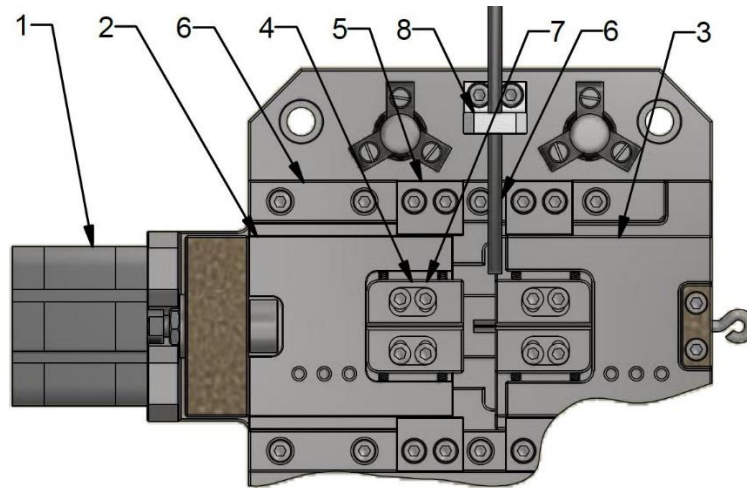


Fig 8.11 Conduit immobilizing and grooves making system.

8.3.8 Clamps and springs system

Two pairs of clamps, mentioned in previous subchapters, have mobility in the axis parallel to the conduit. Clamps must be movable (due to springs system) due to two reasons:

- do not leave any space in the cover between where its cut and the beginning of markings;
- to avoid sliding cover along the inner cords during cutting (clamps move both sides, holding the cover when the top blade pushes them);

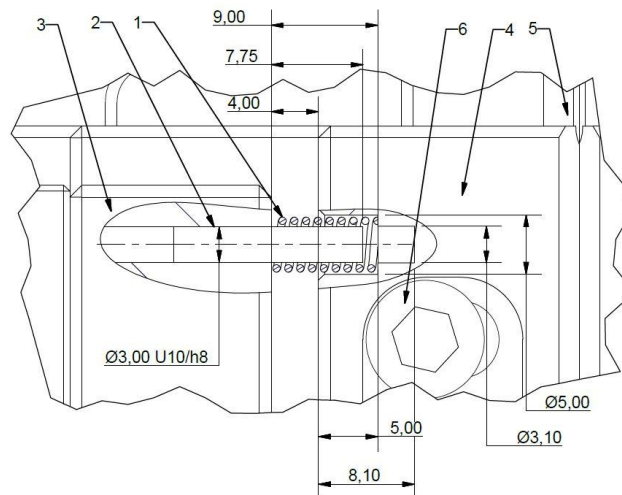


Fig 8.12 Section view of clamps and springs system.

The whole system contains four separable symmetrical groups of parts, which allow the clamps to move translationally (Fig 8.12). Each clamp (4) is fixed to the sleigh (3) with a pair of screws (6), however each of them makes minimal contact between head and the clamp surface, to avoid unwanted drag. The sleigh have holes with pins (2) inside and springs (1) inserted on the pins. There was a need to select proper springs for this application, fulfilling the requirements:

- outside diameter equal or lower than 5,5 mm;
- maximum length below 12 mm;

- stiffness coefficient appropriate to overcome the drag and return to default position;
- Permitted deflection at least 3 mm;

Selected springs are in accordance with standard DIN 17223 [33]. They possess parameters presented in Table 8.1.

Table 8.1 Springs parameters.

Parameter	Value
initial length, l_0 :	9,6 mm
maximum deflection, Δl :	3,8 mm
nominal diameter, D_n :	4,0 mm
hole diameter, D :	5,0 mm
pin diameter, d :	3,0 mm
wire diameter, d_w :	0,63 mm
material:	Stainless steel
stiffness coefficient, c :	4,55 N/mm

Based on values shown in Table 8.1 and Fig 8.12 it was decided to apply initial tension of the spring equal to $\Delta l = 0,6 \text{ mm}$, what gives axial force F_x equal to:

$$F_x = 2 * c * \Delta l = 2 * 4,55 \frac{\text{N}}{\text{mm}} * 0,6 \text{ mm} = 5,46 \text{ N} \quad (8.2)$$

The value is big enough to overcome drag (in case the screws being in minimum contact with clamps). What is more, it is easy to see that when the blade gets between clamps, the extreme deflection is under maximum value and it is equal to 3,6 mm. Tight fit $U10(-\frac{18}{58})/h8(-\frac{0}{-14})$ [XXXVII] was used in this application, does not allowing the pins to move along the hole [35] (pins already have the tolerance in accordance to standard ISO 2338). For clarity the render top view of clamps system is shown in Fig 8.13.



Fig 8.13 Render image: clamps and springs system.

8.3.9 Frame construction

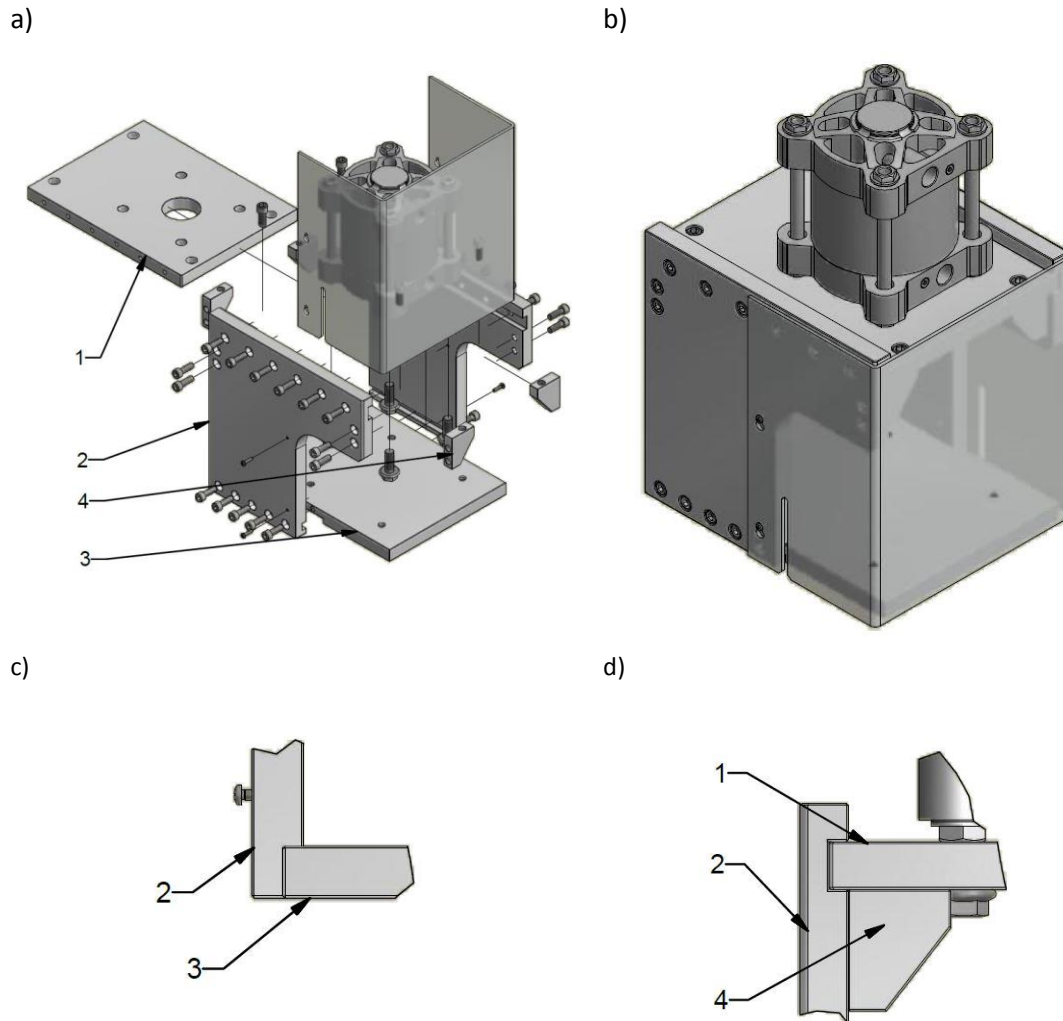


Fig 8.14 Frame construction: a) exploded view, b) assembly view, c) bottom connection, d) top connection.

Among a couple the frame types (screwed profiles, welded frame, etc.) the simplest construction was chosen. It contains the four aluminum plates (Fig 8.14 a), b)): 1 - to which the cylinder is screwed, two symmetrical wall plates (2) and the table plate (3). All parts are joint together with the same screws (M12x30). During cutting process, the cylinder loads the frame with vertically orientated force; for better load distribution special rows in wall plates were designed (Fig 8.14 c), d)). Bigger stiffness of the frame was achieved due to brackets application (4).

8.3.10 Protection

The only dangerous areas for operator are front and back side of the machine. Both of them must be safe: back side was covered with 0,5 mm aluminum plate, but more sophisticated system was designed for the front panel (Fig 8.15 a)). Transparent, plastic, 5 mm thickness protection (1) is fixed to the trolley (2, *Hiwin, MGW-07H* [37]), which can move up and down along the trails (3). Operator can easily pick the protection up with handler system (4). This solution does not require any tools during using it due to two pairs of clips (3,5, Fig 8.15 a)). Clip 3 is connected directly with handle (1), but with a pair of springs (4), which allow the system to

work as a mechanism in pens (pen's refill goes up and down and is blocked in both positions due to springs and clips). Operator can let the protection goes down by pulling both handles (the shield runs down along the guidelines, the drop is muffled thanks to pieces of rubber glued from the bottom).

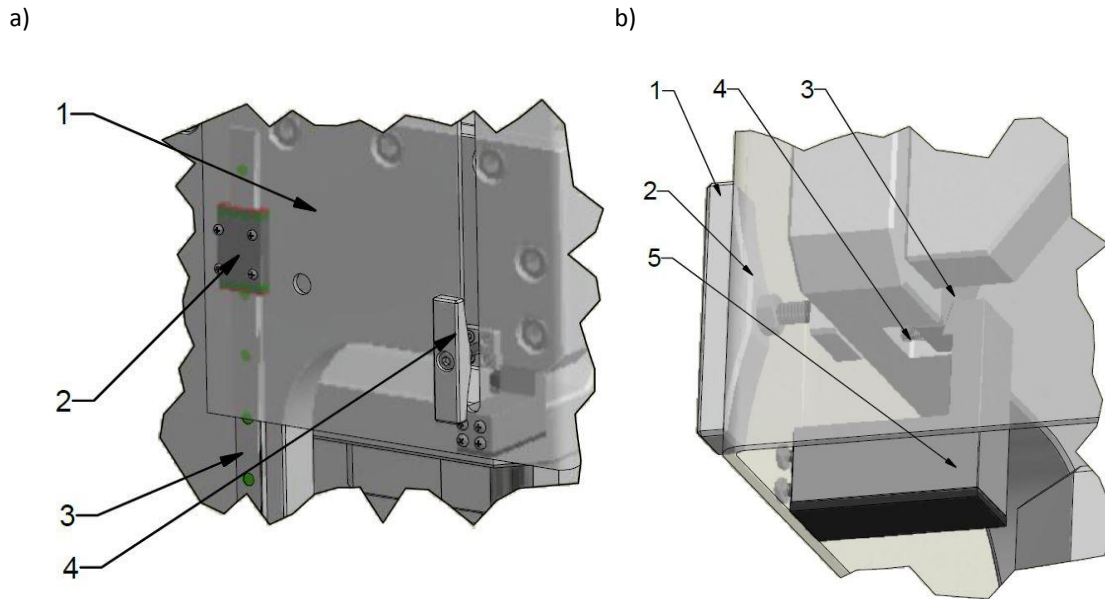


Fig 8.15 Protection construction: a) guidelines and plastic protection, b) pull up – release mechanism.

Taking into account that the need of maintenance service appears very seldom, the primary version of system was considered as too expensive and replaced with simple protection and four screws, which can be seen on Fig 8.14 b).

8.3.11 Smart systems

According to client requirements there was a need to create some systems, which allow the operator having easy access to both of blades and the whole tooling with eliminating necessity of frame disassembling. Three solutions which limit mounting and dismounting steps of tooling were designed:

- taking out all the tooling system contains three activities (Fig 8.16): taking out 4 screws on the bottom plate (a1), loosen piston's nut (a2), taking out two screws fixing top blade assembly (a3);
- the second system is the most complicated, because of hard access to the blade, which is in the very center of the machine. It contains following steps: loosen four screws holding the sleigh (b1), taking out two screws fixing sleigh to the trails (b2), loosen single screw from the plate, holding the plate (b3), taking out pair of screws holding one part of blade housing (4), loosen screw, which fixes blade and taking out the blade (b6) and shims (if exist);
- the purpose of the third system is taking out top blade housing and adjust its position. The operations involve: taking out or loosen screws shown on Fig 8.18 in order c1-c4 and taking out the blade (c5). However, to take out only the blade, it is only necessary to loose fixing screw (c4) and blade should fall out itself.

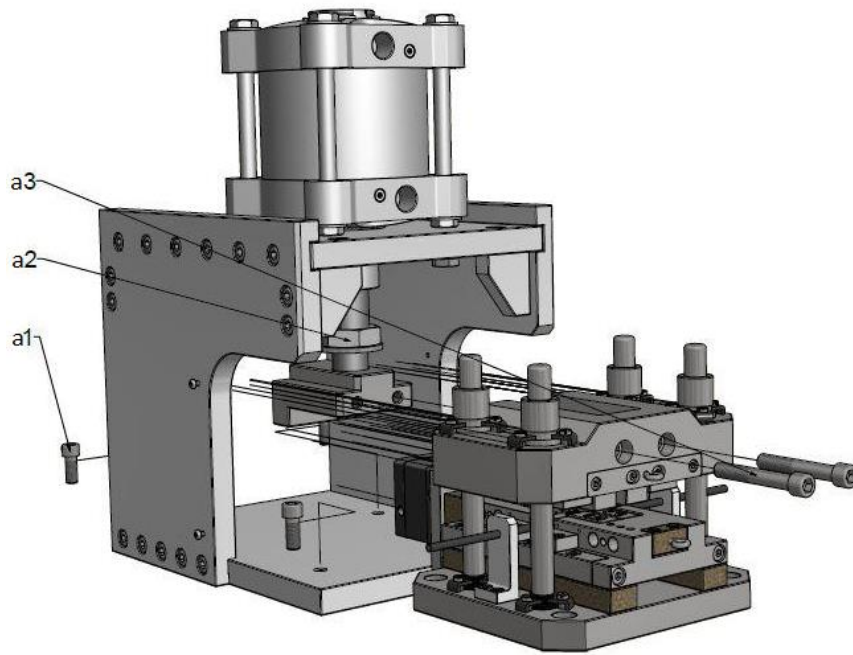


Fig 8.16. Dismounting all the tooling.

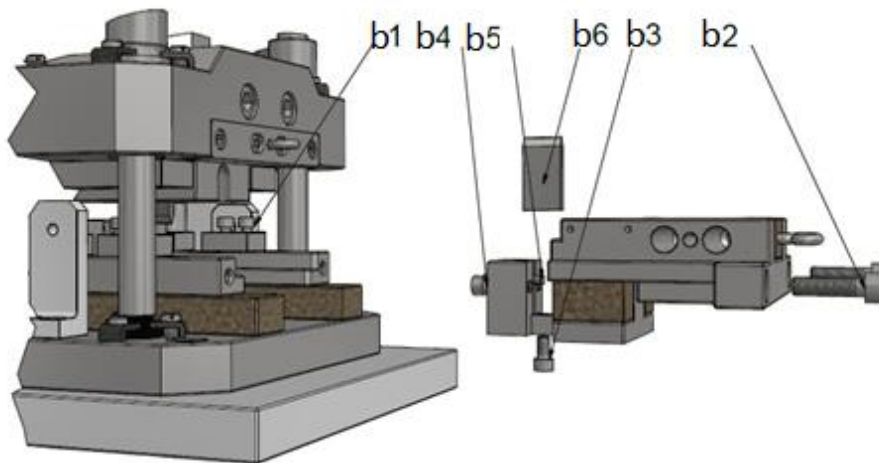


Fig 8.17. Dismounting bottom blade.

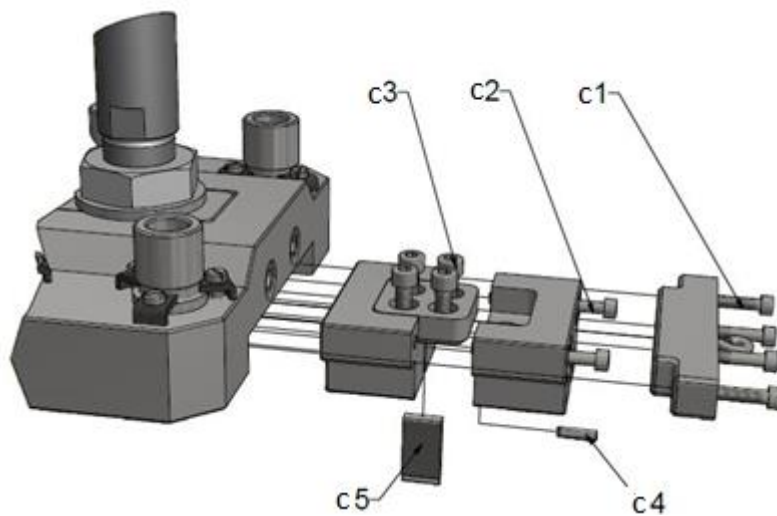


Fig 8.18. Dismounting top blade.

8.4 Budgeting

This section is a description of total costs calculation. However it does not include any electronic or pneumatic components costs, only these elements, which were mentioned in this chapter. To estimate total cost of production of the machine, three main things were considered: material, production, purchasing parts. After the research of prices and estimating costs of production, all parts that will be manufactured were divided into 3 classes:

- 1st class – estimated time of production lasts no longer than 1 hour (average 45 min);
- 2nd class – estimated time of production lasts no longer than 2 hours (average 90 min);
- 3rd class– estimated time of production lasts no longer than 4 hours (average 180 min);

The classification was made after consulting technicians team. Table 8.2 contains all information around masses of materials, prices, amounts of hours predicted and all costs. Also a research around purchasing parts was made. All products were found on sellers website and compared. Information about all equipment was included in Table 8.3. The amount of material was increased by 40% due to material waste and predicted mistakes.

Table 8.2 Cost of material and manufacturing.

ca	Aluminum	Steel	Celeron	Total
price/kg (EUR)	6	1,8	12	
amount of kg increased by 40%	33,35	53,5	0,515	
price of material	200,1	96,2	6,18	302,508
price for 1 hour of manufacturing (EUR)	12	10	10	
No. of items of 1st class	6	17	3	
No. of items of 2nd class	1	12	3	
No. of items of 3rd class	4	3	0	
total amount of machining hours	18	39,8	6,75	
total cost of machining (EUR)	216	398	67,5	681
total cost of production (EUR)				983,51

Table 8.3 Cost of purchased parts.

Name	No. if items	cost of 1 item (EUR)	cost of all items (EUR)
DSBG-160-25	1	580	580
DSBG-160-25	1	140	140
ECO-4	4	25	100
EBU-17-Medium	4	30	120
Blades	6	35	210
Cartridge heaters	4	10	40
Thermocouples	4	15	60
		total (EUR)	1250

Total amount of all expenses is evaluated as around 2300 EUR. Cost of parts like nuts, washers, bolts, pins, springs, screws is also included as standard parts (see Fig 8.19).

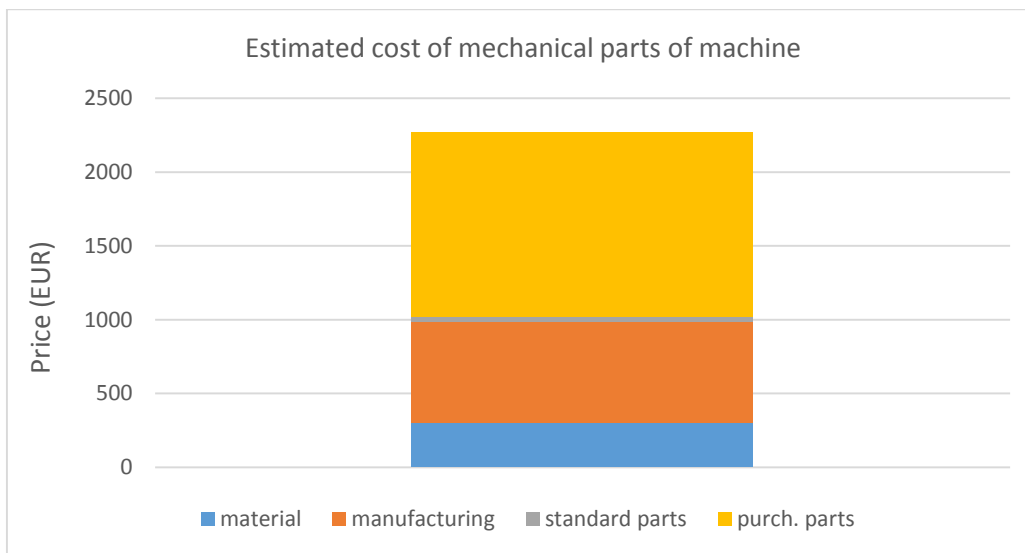


Fig 8.19 Estimated cost of mechanical equipment of machine.

8.5 Critical analysis and prospects of improvement

Project realization will probably be made in February 2016. Until this time there is no certainty around perfect, irreproachable work of the machine. Taking into account rather simple construction and low complication level of the process it makes us think that no unexpected failures or imperfections will turn out during first tests.

All doubts about project results are caused by two reasons. First: the whole solution concept was based on experience of company expert who has experience with similar machines used for cutting cables. Known solutions with very high probability will turn out to be rightful, but on the other hand they do not must be the best. If I had more time (the total amount of days spent with that project was no longer than 15, because of more urgent duties) I would make deeper research around solutions known in industry.

Furthermore, I would verify the concept of cutting blades and hearing system, using some of dynamic simulation tools which could verify if heating power is suitable, how to control the current flowing thru cartridge heaters to optimize temperature. The knowledge about change of dimensions caused by temperature increase would also be well seen. A trial (simulation) of cutting process could give information about the really needed force and results of the process.

What I would have done to improve the project is application of some spring system (absorber) for dumping the force loading construction during cutting. That would increase durability of blade system in low-cost way. The same thing is with adjusting the machine construction to existing model of the rest of manufacturing cables system, what could reduce e. g. size of frame construction and space taken by the whole machinery. Table 8.4 is a summary of the critical analysis included in this subchapter. It contains mainly the evaluation of project in far-field taken from higher point of view.

Table 8.4 SWOT chart for project.

<p style="text-align: center;">Strengths</p> <ul style="list-style-type: none"> • simple structure of machine; • low cost of production; • meeting all of needs of client; • all undesirable situations predicted; • lots of promotional tools (animations, renders) for marketing needs; 	<p style="text-align: center;">Weaknesses</p> <ul style="list-style-type: none"> • no certainty of full success of the prototype; • finding optimal adjustable process parameters requires long trials;
<p style="text-align: center;">Opportunities</p> <ul style="list-style-type: none"> • properly working prototype can open the way for starting production of the machine in bigger amount items, start of serial production for different applications (e. g. electric wires); • gaining precious experience of company employees in this quite narrow (specialized) field of industry; • the company may be more recognizable and have better opinion on international market; 	<p style="text-align: center;">Threats</p> <ul style="list-style-type: none"> • failure of cutting system (unpredicted damages of conduit, which means re-designing the machine from basic concept); • ribs not projecting grooves in good enough shape (need of make another, detailed machined parts – longer time and costs); • Loss of confidence in Company's quality (in case of failures);

8.6 Maintenance guidelines

To give the machine best chances during manufacturing process and after assembling, during normal work, a group of procedures and maintenances must be done.

8.6.1 Documentation

First step is to take care about technical documentation (2D drawings of parts). All parts should be kept in company's server in rightful order and files organization:

- name of folder as followed: *207-15-cutting_press*, where *207* is the number of project and *15* is last two digits of the year;
- machine is divided into subassemblies-models, codified: *xxx-name*, where *xxx* are three digits of subassembly number (e. g. *013-press_base*); the main folder contains the entire assembly and folders with subassemblies having the same name as models of those subassemblies; standard, buying parts have separated folder and it does not matter to which subassembly those parts belong;
- each folder of subassembly contains 3D model of the subassembly, 3D models of all parts that the subassembly contains and drawings; models and drawing defining the part must always have the same name, which is *zzz-yy-xxxww*, here *zzz* is number of project, *yy* is the year, *xxx* is number of subassembly and *ww* is number of drawing in this subassembly (e. g. *207-15-01304*);
- only one folder with project can be found on server, no extra copies for revisions or other needs;
- main folder contains an *.xls file with table of changes; all changes, including change of dimensions, material, additional part, etc. must be found there with information about date of change, name of person who made that change and clear description of the change.

8.6.2 Manufacturing and assembling

There is a lot of geometrical tolerances included in parts of this project. That is why during production all dimension should be checked and verified. On the drawings taken to production hall, during manufacturing, all measured dimensions should be written on the drawing for higher certainty and to reduce chances to make a mistake. Also in case of montage or work failure it will be easier find the source of problem: if it belongs to tolerating chain (and some corrects on drawings are required) or if the part was machined improperly what means the need of corrects.

During assembling the system workers should follow exploded views of machine parts and animations, where the way and order of assembling parts was clearly shown. In case of some troubles with fitting, first thing they should check is the geometry of manufactured parts. If it is made properly, they should contact with drafters and constructors.

8.6.3 During normal work

Most important thing to control is the use of cutting tool. After manufacturing blade have very sharp edge that will get blunt during thousands of work cycles. For that reason they require sharpening and shims application due to dimensions change. Verification of blades should be done two ways: visual inspection and watching conduit ends shape. Service is required in case at least one of them (especially this second one) does not pass inspection. Use of forming clamps is not expected, but visual inspection of grooves combined with temperature monitoring is requested. After any services done in tooling staff, the proper positioning of top blade system is required. For the reason mentioned in previous subchapter and shown on Fig 8.18 screws and plate can adjust position of the blade. Linear sliding bushings require periodical lubrication. Those elements do not work in hard circumstances: no high speed and only axial displacements, no big loads (theoretically forces equal zero), no acidic environment. That is why lubrication should be apply at least every 200 thousands cycles (once a week). Standard type of lithium grease or with polytetrafluoroethylene (PTFE) would be recommended.

9. Concluding remarks

The internship that I was participating during this semester was my third work experience in profession of mechanical engineer, and in many fields: the most precious. The thing, that was completely new and valuable was the trust of managers and supervisors and responsibility related to it. I received many tasks from different field of mechanics: machines design and development, safety system improvement, engaging basics of physics and mathematics to solve real problems, production line development, creating a test station. First time I got my chance to really show some of my best skills and improve them dynamically.

During this period of 4 months I trained my imagination and creativity used for designing and construction, learned some basics of pneumatic systems, gained proficiency in *Solidworks* and *Inventor* software and discovered tools unknown for myself: like rendering or motion simulations. Colleagues from *PR* showed me how to make drawing in another way than GD&T standard, the way that make manufacturing process faster and easier for workers not familiar with international standards. I also tasted consequences of making mistakes and learned more about value of decisions. I learned how to construct something without new, expensive, hi-technologies, which make everything faster and easier, but how to use simple tools to achieve the same effect.

Working with Portuguese people I consider definitely positive. The vast majority can be described as helpful, open-minded, trustworthy, hard-working. They absolutely broke a Polish stereotype of quite lazy, southern nation, for which more valuable are holidays, long siesta and full stomach, than work, ambitions and goals. They are reliable titans of work, which at the same time can be cheerful and smiling, enjoying life. People in *PR* (those with whom I have worked the longest time) treat me like one of them, on friendship level.

ISEP Master Degree in Mechanical Engineering department gave me a chance for gathering work experience that is very hard to meet in my Country, where a student can count only on minimal support from universities. What is more the employees of ISEP really care of foreign students and try to do their best not only in field of studies, but also in range of their entire life in Portugal. I am glad, that I could taste this adventure and there is nothing to regret.

10. Bibliography and others sources of information

10.1 Books and scientific papers

In order of appearance in the report:

- [1]. Hecht E., *Optics*, Addison-Wesley, 2002.
- [2]. UCSB Environmental Health and Safety, *Laser Safety Manual*, internet access dated 2-11-2015.
- [3]. Miller S., *Teoria maszyn I mechanizmów, Analiza układów kinematycznych*, Oficyna wydawnicza PWR, 2002.
- [4]. Mays W. L., *Hydraulic Design Handbook*, McGraw-Hill Education, Chicago, 2004.
- [5]. HIWIN Company, *HC-07-4-PL*, producer catalog.
- [6]. Festo Company, *Round cylinders: DSNU, DSNUP, DSN, ESNU, ESN*, producer catalog.
- [7]. Group work, *Mały poradnik mechanika T. 1.*, WNT, 1984.
- [8]. Wayne Beaty H., Kirtley J. L., *Electric Motor Handbook*, New York, 1998.
- [9]. Blake A., *Handbook of mechanics, materials and structures*, John Wiley and sons, London, 1985.
- [10]. Gewert M., Skoczylas A., *Analiza matematyczna 2, przykłady i zadania*, Wrocław 2002.
- [11]. Bell D. A., *Electric Circuits*, Oxford University Press, 2008.
- [12]. Festo Company, *Guided drives DFM, DFM-B*, producer catalog.
- [13]. Festo Company, *Flow control valves GRLA-...-RR, CRGRLA-...-RR*, producer catalog.
- [14]. Festo Company, *VUWG*, producer catalog.
- [15]. Festo Company, *On-off/soft-start valves HE/HEE/HEP/HEL, D series*, producer catalog.
- [16]. Festo Company, *Filter regulator for D-Micro series LFR-...-D-5M-MICRO-RR-SA*, producer catalog.
- [17]. Festo Company, *Front panel valves SV*, producer catalog.
- [18]. Szczuka J., Żurowski J., *Materiałoznawstwo przemysłu drzewnego*, Wydawnictwa Szkolne i Pedagogiczne, 1995.
- [19]. BMW AG, *Repair manual: C1, C1 200*, BMW Motorrad After Sales UX-VS-2, Germany, 2001
- [20]. Letier P., Schiele A., Avraam M., Horodinca M., *Bowden cable actuator for torque-feedback in hepatic applications*, Eurohaptics 2006 conference.
- [21]. Patent, Kawasaki J., Kabushiki K., US4872293, USA, 10-10-1989.
- [22]. Patent, Houldcroft P., T., *Laser cutting apparatus*, US3569660A, USA, 9-03-1971.
- [23]. Asundi A. K., Rastogi P. K., *Optics and lasers in engineering*, Elsevier, 1999.
- [24]. Patent, Mohan M. V., Wenzhuo Y., Tieu A., Baolin R., *Ultrasonic waterjet apparatus*, US8006915B2, USA, 30-08-2011.
- [25]. Patent, Ducret L. C., *Automatic cable measuring and cutting machine*, US4476754, USA, 16-10-1984.
- [26]. Patent, Ing. C. Olivetti & Co., S.p.A., *Machine for cutting and stripping back electric wires and cables*, US3727492, USA, 17-04-1973.
- [27]. Patent, Makfil System, *Machine for cutting and stripping electric cables*, Italy, EP 1 667 296 A2, 02-12-2006.

- [28]. Patent, Malm E., O., Cutting strips, cutting die knives, cutting rules and the like, US3411208, USA, 19-11-1968.
- [29]. Hartink A., E., *Complete encyclopedia of Knives*, Lisse, The Netherlands: Chartwell Books, 2005.
- [30]. Hwang K. C., Lee S., H. C. Lee, *Effects of alloying elements on microstructure and fracture properties of cast high speed steel rolls*. Elsevier Science S.A, 1998.
- [31]. Bayer A. M., Becherer B., A., T. Vasco, *High-Speed Tools Steels*, ASM International, 1989.
- [32]. Thorne J. L., *Technology of thermoforming*, Carl Hanser Verlag GmbH & Co. KG, 1996.
- [33]. Srihar K., Ganesh Babu K., *Design of machine 2e*, Tata McGraw Hill Education Private Limited, 2009.
- [34]. Festo Company, *Cylinders DSBG to ISO 15552*, producer catalog.
- [35]. Alcomex Company, *Sprężyny naciskowe (...) zgodnie z PN-71/M-80057 (EN 10270:1-SH oraz DIN 17223, C; nr mat. 1.1200)*, producer catalog.
- [36]. Festo Company, *Compact cylinders AND, AEN, to ISO 21287*, producer catalog.
- [37]. Hiwin Company, *Hiwin kompakt*, producer catalog.

10.2 Internet sources

In order of appearance in the report:

- I. http://www.rofin.com/fileadmin/user_upload/FL_09062015_eng.pdf, access dated 04-11-2015.
- II. <http://student.mvlab.pl/pliki/lasery/TL-MTR/TL-W2.pdf>, access dated 02-11-2015.
- III. [http://www.mif.pg.gda.pl/kfamo/LM/FT/TL01_bezpieczenstwo%20pracy%20z%20laserami%20\(01-24\).pdf](http://www.mif.pg.gda.pl/kfamo/LM/FT/TL01_bezpieczenstwo%20pracy%20z%20laserami%20(01-24).pdf), access dated 04-11-2015.
- IV. http://www.lasersafetyindustries.com/Laser_Safety_Signs_Class_4_3r_3B_s/4.htm, access dated 03-11-2015.
- V. http://www.lasersafetyindustries.com/Laser_Safety_Face_Shields_s/139.htm, access dated 03-11-2015.
- VI. http://www.lasersafetyindustries.com/Laser_Safety_Glasses_Goggles_and_other_laser_protection_s/3.htm, access dated 03-11-2015.
- VII. <http://www.lasersafety.com/barriers>, access dated 03-11-2015.
- VIII. http://www.lasersafetyindustries.com/Laser_Safety_Barrier_and_Curtains_s/2.html, access dated 03-11-2015.
- IX. https://www.thorlabs.com/NewGroupPage9.cfm?ObjectGroup_ID=4372, access dated 03-11-2015.
- X. <http://www.kenteklaserstore.com/free-standing-laser-barriers.aspx>, access dated 03-11-2015.
- XI. <http://www.lasersafety.com/windows/laser-safety-windows>, access dated 03-11-2015.
- XII. <https://www.rli.com/resources/articles/classification.aspx>, access dated 08-12-2015.
- XIII. <https://www.sick.com/pl/pl/czujniki-zblizeniowe/indukcyjne-czujniki-zblizeniowe/iq08-04npokw2s/p/p282621>, access dated 04-01-2016.
- XIV. <https://pl.wikipedia.org/wiki/Wyboczenie>, access dated 05-01-2016.
- XV. http://wbia.po.opole.pl/zadania/fm/2.5_Wyboczenie.pdf, access dated 04-01-2016.

- XVI. https://www.festo.com/net/en_corp/SupportPortal/default.aspx?cat=1702&q=vz-3-pk-3&documentId=316617&tab=3&s=t, access dated 06-01-2015.
- XVII. <http://pobox.mech.pk.edu.pl/~hsa/Kszaltowniki%20zamkniete.pdf>, access dated 6-12-2015.
- XVIII. <http://www.decorativesurfaces.org/products/medium-density-fiberboard.html/details/>, access dated 10-01-2015.
- XIX. <http://www.nwmotion.com/Portals/0/BE/SBgantry300x278.jpg>, access dated 8-10-2015.
- XX. http://img.directindustry.com/images_di/photo-g/24902-5175187.jpg, access dated 8-10-2015.
- XXI. <https://upload.wikimedia.org/wikipedia/commons/b/b0/Bowden.jpg>, access dated 10-01-2016.
- XXII. http://www.scs-cablesystems.com/index.php?option=com_content&view=article&id=67&Itemid=10&lang=en, access dated 11-01-2016.
- XXIII. http://www.drallim.com/drallim-share/pdf/DCB0010_Cable_brochure.pdf?pdf=DCB0010_Cable_brochure.pdf, access dated 11-01-2016.
- XXIV. <http://www.gsp.info/pl/Noze-tarczowe/>, access dated 15-01-2016.
- XXV. <https://ezesharp.com/knife-blade-types/>, access dated 16-01-2016.
- XXVI. http://www.directindustry.com/prod/starcut/product-54555-1690517.html#product-item_958545, access dated 16-01-2016.
- XXVII. <http://www.caknife.com/shape/22/Straight-Blades.aspx>, access dated 16-01-2016.
- XXVIII. https://en.wikipedia.org/wiki/List_of_blade_materials#Other_materials, access dated 16-01-2016
- XXIX. <https://en.wikipedia.org/wiki/Polyethylene>, access dated 16-01-2016.
- XXX. <http://www.4m-association.org/content/hot-embossing>, access dated 16-01-2016.
- XXXI. <https://www.imt.kit.edu/img/abformung1.jpeg>, access dated 16-01-2016.
- XXXII. <http://demand.cbeyondhosting2.com/multicut.html>, access dated 16-01-2016.
- XXXIII. http://www.coferac.com/site/index.php?page=shop.browse&category_id=27&option=com_virtuemart&Itemid=135, access dated 11-01-2016.
- XXXIV. <http://www.resisterma.com/en/produtos> access dated 21-01-2015.
- XXXV. <http://www.laminex.com.br/data/imagegallery/5a960599-6765-78c3-7933-d9f0b279d527/539d1ded-07b9-01ce-9c7e-ce584d7e1abd.jpg>, access dated 11-01-2016.
- XXXVI. <http://solutions-in-plastics.info/en/products/composites/>, access dated 11-01-2016.
- XXXVII. <http://www.pkm.edu.pl/index.php/component/content/article/84-tolerancje/277-00010332>, access dated 11-01-2016.

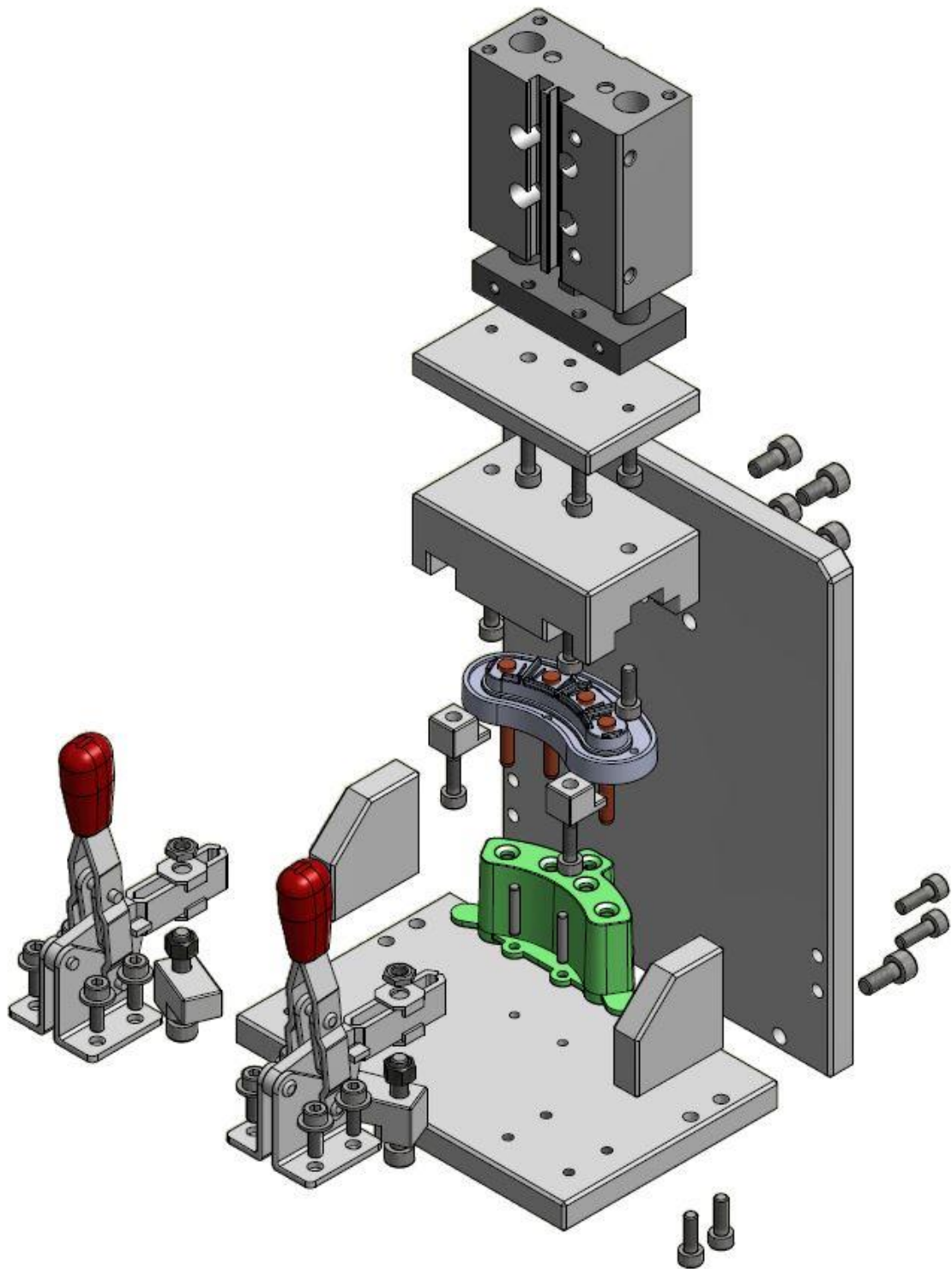
Appendix

Following section presents views of assemblies and exploded views of all projects presented in this work. However in case some assemblies were shown clearly enough in the chapters, they were not included here. All attachments are listed below:

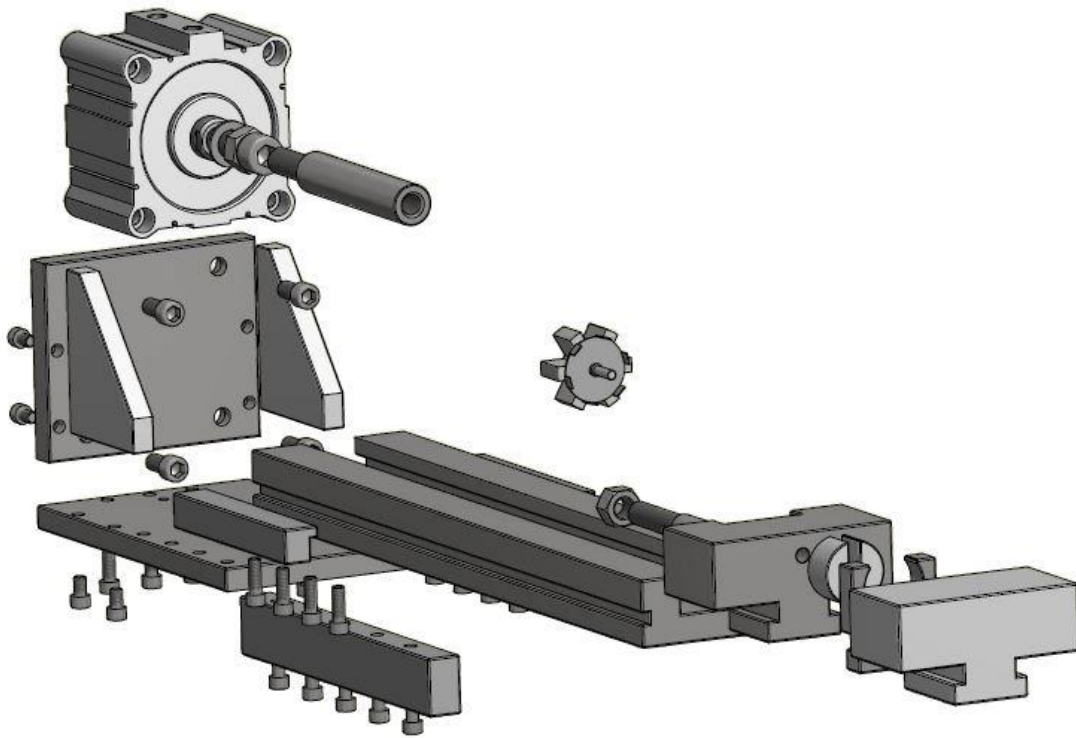
Attach. 1. Laser chamber closing door (assembly view)	86
Attach. 2. Connector test station (exploded view)	87
Attach. 3. Milling machine improvement (exploded view).....	88
Attach. 4. Milling machine improvement (assembly view).....	88
Attach. 5. Press, assembly view without front shield.	89
Attach. 6. Piston rod and top blade subassembly (assembly view)	90
Attach. 7. Piston rod and top blade subassembly (exploded view)	90
Attach. 8. Bottom blade subassembly (exploded view).....	91
Attach. 9. Bottom blade subassembly (assembly view).....	92



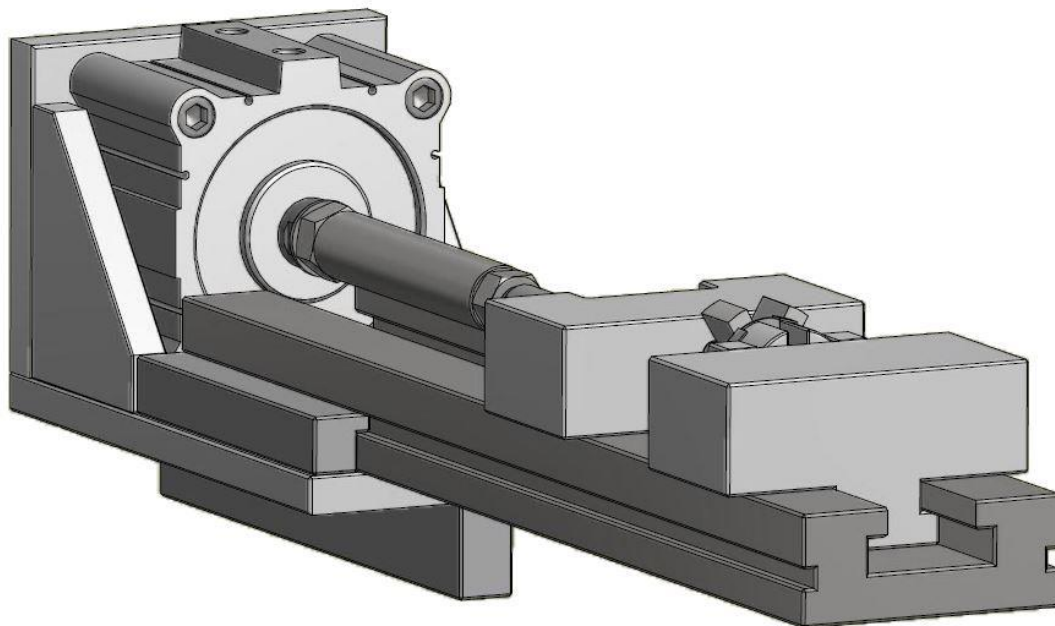
Attach. 1. Laser chamber closing door (assebly view).



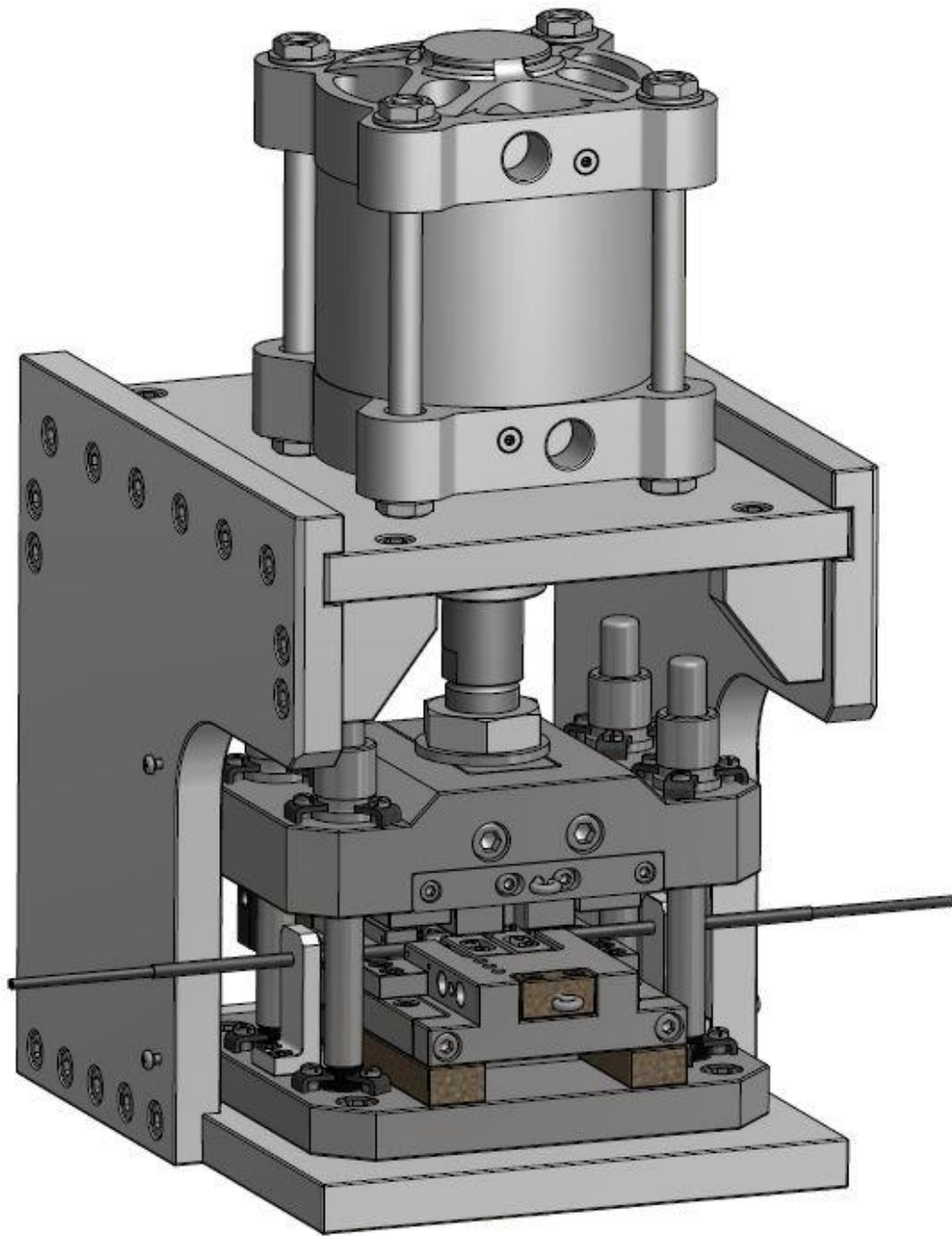
Attach. 2. Connector test station (exploded view).



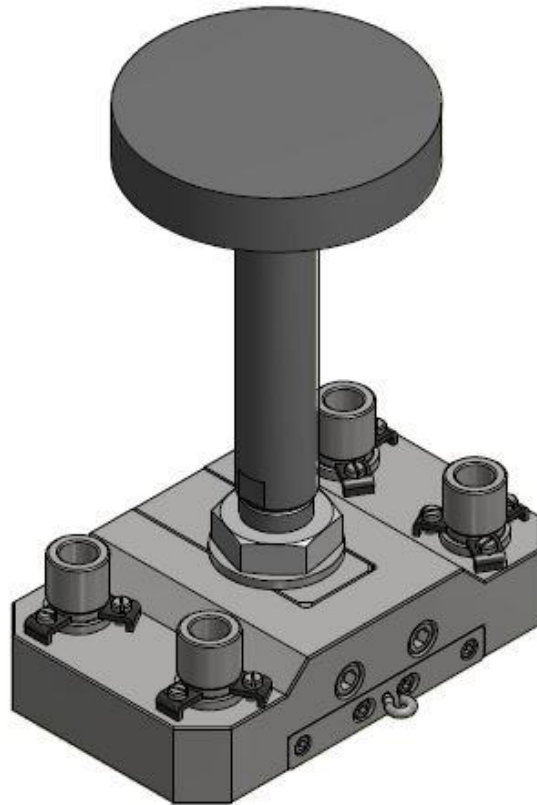
Attach. 3. Milling machine improvement (exploded view).



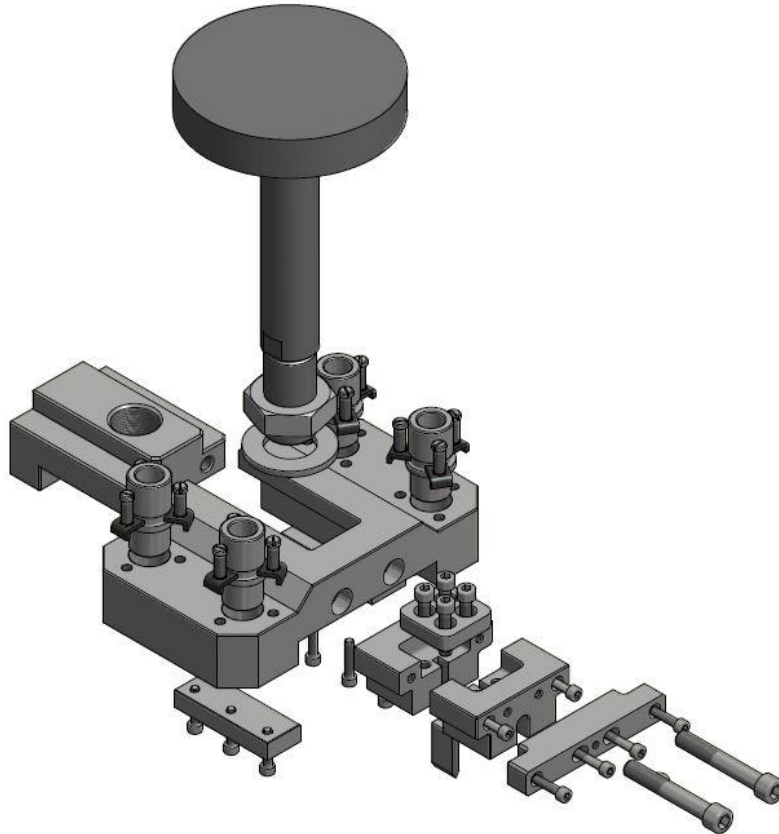
Attach. 4. Milling machine improvement (assembly view).



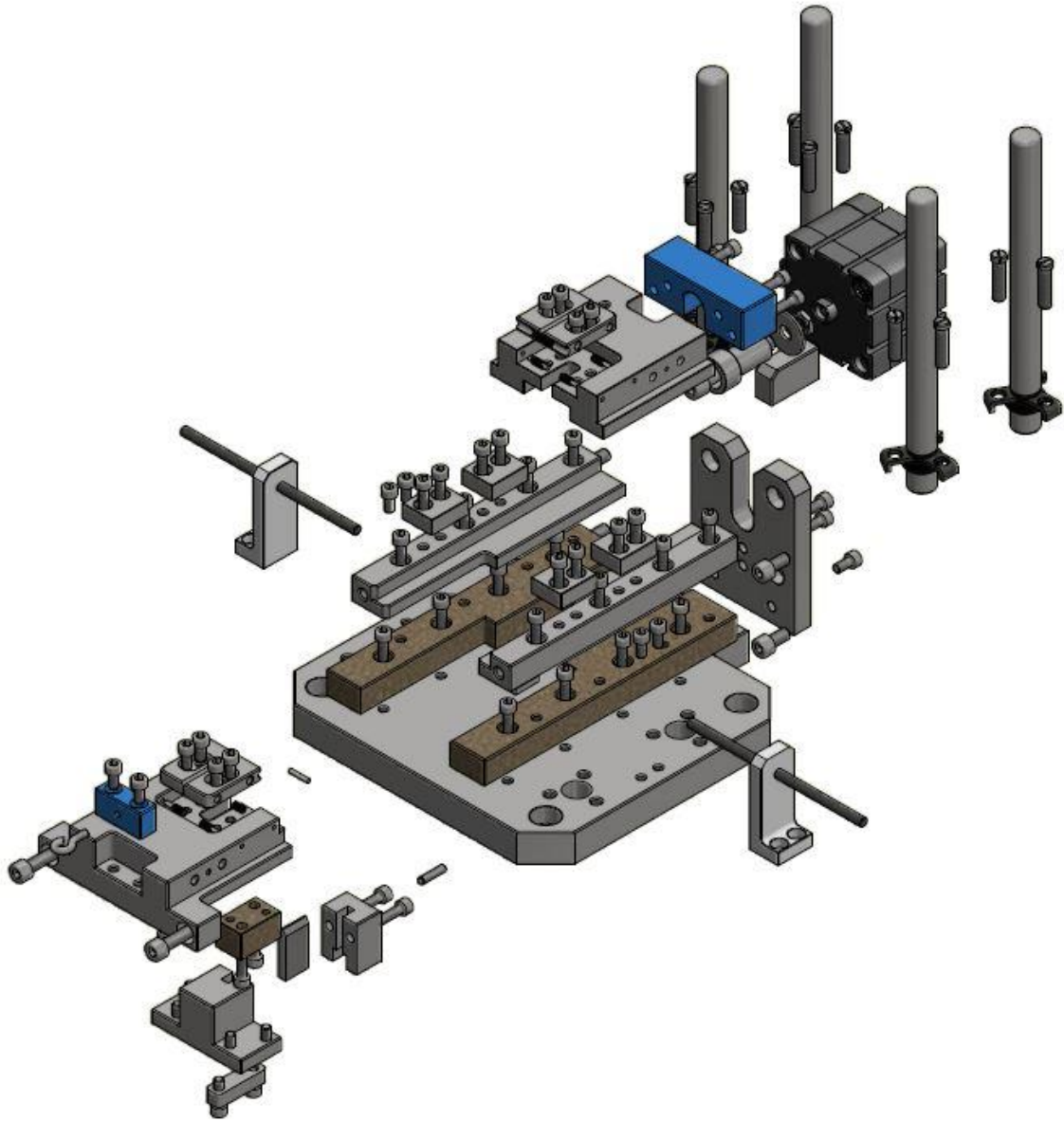
Attach. 5. Press, assembly view without front shield.



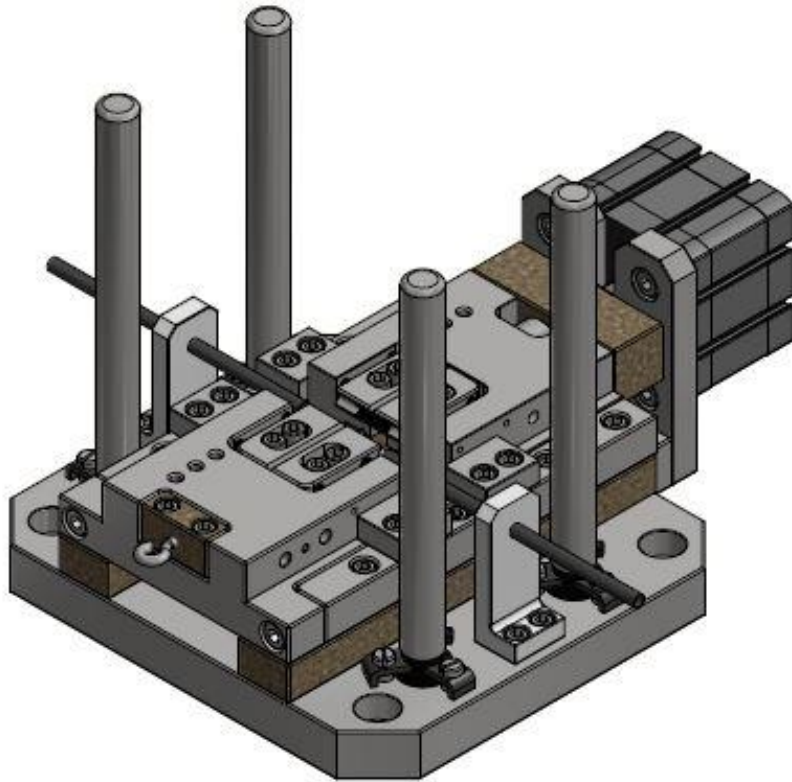
Attach. 6. Piston rod and top blade subassembly (assembly view).



Attach. 7. Piston rod and top blade subassembly (exploded view).



Attach. 8. Bottom blade subassembly (exploded view).



Attach. 9. Bottom blade subassembly (assembly view).