AUTOMATING THE WELDING PROCESS OF COMPOSITE SHEETS AND CONCEPT DESIGN OF A CUTTING MACHINE

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ABSTRACT

This thesis is a part of a factory expansion project where the commissioning party (Admor composites Oy) wanted a new automated welding process plant to fulfil their need of manufacturing new transportation tanks with added sheet width. The project also aimed at reducing the number of workers and at cutting down the physical stress on the welding operator.

Admor Composites manufactures composite structured transportation tanks to transport liquid cargo and food products by road. When the company experienced a demand for new tanks with larger volumes, it decided to tackle the problem by increasing the composite sheet width, which led to a need for a new welding machine. To deal with the changes, the company needed a solution, which would allow them to optimise the welding process, thus increasing their productivity.

This thesis aimed at providing Admor Composites Oy with an optimal idea and a concept design for a cutting machine to automate the welding process and to overcome the new challenges faced by the company.

Keywords Automation, Butt Fusion Welding, CNC router Composite Sheet, Transportation tanks

Pages 29 pages

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1 INTRODUCTION

Transportation tanks are used for liquid transportation and food products designed to fit most standard truck beds. Admor composites manufactures top-class composite structured transportation tanks. Their products are ADR (the European Agreement concerning the International Carriage of Dangerous Goods by Road**)** approved and are designed to transport liquid cargo and food products by road. The history of composite products dates to 1969. Their first products were manufactured in 2001 at Muovityö Hiltunen Oy. The whole process, including product development and prototype manufacturing, culminated in 2010, when the product range was ready for mass production and a new company was founded to meet the growing demand. (Admor Composites, n.d.)

According to the company's CEO, they receive composite sheets of different sizes from their supplier. They butt-fusion weld those sheets, cut out the welding seams after it is cooled enough and trim the edges to get a single unit of sheet of desired dimension. The maximum width of the sheets to be welded was 4 meters but because of a new demand of tanks with slightly larger volume, the maximum width is increased by 1 meter. Currently, only the welding is done automatically whereas feeding the sheets into the welding machine, shearing the welding seams and trimming the edges are done manually. Having to do it manually is not only time consuming but also tiring and takes a lot of physical effort. To overcome these complications, they wanted to automate this whole process and optimize the manufacturing.

This thesis includes systematic solution of individual process and a concept design that automates the whole system. The new design should optimise the welding process as well as reduce physical stress on the operator.

2 THEORY

2.1 Transportation tank

Since these tanks are used to transport liquid cargo and food products, they should be light in weight, durable, safe, practical and productive. Admor Composites offers four different kinds of tanks and example of which is shown in figure 1.

Figure 1. Transportation tank (Admor Composites, n.d.)

Tank options are as follows:

- Demountable SWAP
- Truck tank
- Drawbar trailer
- Semi-trailer

(Admor Composites, n.d.)

General characteristics of the tanks according to Admor Composites are:

1. Light weight
    - Demountable swap body tank (31,000 litre – 2000 kg)
    - ISO 20ft. container (25,000 litre – 2600 kg)
    - Semi-trailer (38,000 litre – 6000 kg)

2. Chemical resistance

Tanks that are conform to ADR 2017 classification are designed to transport harsh chemicals such as:

- 1789 Hydrochloric acid
- 1791 Hypochlorite solution
- 1824 Sodium hydroxide
- 2582 Ferric chloride solution
- 1830 Sulphuric acid
- 2031 Nitric acid

- 1779 Formic acid
- 2581 Aluminium chloride solution

3. Food contact

Tanks comply with the standards set out in EU Food Contact Materials-Regulation (EC) No. 1935/2004 and have been manufactured in accordance with EU Regulation (EU) No. 10/2011.

4. Easy to clean

Since tanks are easy to clean, they are suitable for multi-purpose use. Difficult substances such as latex, do not stick to the inner surface of the tanks.

5. Safety

These products have been tested and proven safe due to the solid sandwich structure of their walls.

To accommodate all the features mentioned above, composite materials are the excellent choice since it also reduces fuel use. Admor composites provides three different structure options: FRP (Fibre reinforced plastic), Thermoplastic and Fluoroplastic. (Admor Composites, n.d.)

2.2 Composite material

Composites, also known as fibre-reinforced plastics (FRP), are defined as materials, which are a combination of reinforcements and matrix. Neither of these are well suited for construction purposes on their own but when combined result in a very strong and rigid material. The matrix protects the fibres from environmental and external damage and transfers the load between the fibres. The fibres, in turn, provide strength and stiffness to reinforce the matrix and help it resist cracks and fractures. (compositeslab, 2016)

Figure 2. Composite material (compositeslab, 2016)

2.2.1 Natural Composites

Both animals and plants contain natural composites. Wood is a composite which is made from long cellulose fibres held together by a much weaker substance called lignin. Cellulose is also found in cotton which is much weaker without the lignin to bind it together. Lignin and cellulose are two weak substances but together they form a much stronger one. (Wong, 2006)

Our bones comprise a hard but brittle material called hydroxyapatite (which is mainly calcium phosphate) and a soft and flexible material called collagen (which is a protein). Collagen, which is also found in hair and fingernails, would not be much use in the skeleton by its own but when combined with hydroxyapatite it gives bone the properties that are needed to support the body. (Wong, 2006)

2.2.2 Early composites

Composites like mud bricks have been around for thousands of years. Mud can be moulded into a brick shape to give a building material. It is strong which means it has good compressive strength, but it is quite brittle and breaks easily which means it has poor tensile strength. Straw acts very strong while stretching it, but it crumples up easily. But it is possible to make bricks with good compressive and tensile strength by mixing mud and straw together and yield excellent building blocks. (Wong, 2006)

Another example of early composite is concrete. A mixture of gravel, cement and sand is called concrete. It has good compressive strength but poor bending strength. Recently, it has been found that adding metal rods or wires to the concrete can increase its bending strength. Concrete containing such rods or wires is called reinforced concrete. (Wong, 2006)

2.2.3 Modern examples

Fibreglass is considered the first modern composite material commonly used for boat hulls, sports equipment, prefabricated building panels and car bodies. The glass is strong but brittle which means it will break if bent sharply. It has been found that mixing glass as reinforcement and plastic as matrix that holds the glass fibres together make up a good composite material with high compressive strength and bending strength. (Wong, 2006)

Composite made by using carbon fibres instead of glass fibres are the most advanced types of composites. They are used in expensive sports equipment such as golf clubs and aircraft structures since these materials are lighter and stronger than glass fibres and costlier to produce. Another example of recent composites are carbon nanotubes. They are even stronger and lighter than carbon fibres but also immensely expensive. They are typically used to make cars and aircrafts lighter. (Wong, 2006)

The world's largest passenger aircraft, Airbus A380, is designed using modern composites. Plastic reinforced carbon fibres are used to make more than 20% of the A380. The aircraft design is the first large scale use of glass fibre reinforced aluminium which is 25% stronger than conventional airframe aluminium but 20% lighter. (Wong, 2006)

2.2.4 Use of composites

Composites give us design flexibility. A new material can be made that meets the exact design requirements by choosing the right combination of matrix and reinforcement material. Modern composites are light and strong which is the biggest advantage, but production cost is still the downside since the raw materials are expensive. (Wong, 2006)

The main reasons to use composite in transportation tank manufacturing are:

- Resistance to chemicals
- Electrical and thermal insulating properties
- High strength-to-weight ratio
- High fatigue resistance
- High impact strength

2.3 **Hot plate welding (Butt Fusion Welding)**

Hot plate welding is a thermal welding technique which uses a heated platen to melt the parts to be welded by pressing them against either side of the heated platen. After the parts are heated to a predetermined temperature, they are brought into contact. The parts are then pressed against each other for a certain amount of time depending on the thickness and material. Ranging from 10 seconds to 1 hour to weld a part, it is considered a relatively slow welding process. However, a carefully performed welding under precise control often yields the weld strength equal to that of parent material. While welding composite materials using this technique, high temperature resins present in composite materials such as Polyether ether ketone tend to stick to the hot plate. (Buxton, 2019)

Figure 3 gives information on heater plate temperature against wall thickness of a sheet. The temperature of the heater plate is chosen according to the wall thickness of the sheet. The heater plate temperature for a 10 mm thick HDPE sheet would be 213°C. (Lauri, 2015)

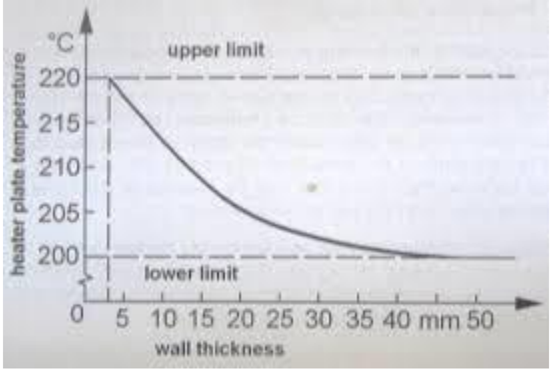


Figure 3. Heater Plate Temperature chart for HDPE (Lauri, 2015)

Table 1. Parameter table for HDPE sheet butt welding

1 Nominal wall thickness s	2 Alignment	3 Heating-up	4 Changeover	5 Joining	
	Heated tool temperature see figure 2				
	Bead height on heated tool on the end of the alignment time (alignment p = 0,15 N/mm^2)	Heating-up time =10 x wall thickness p= ≤ 0,01 N/mm^2)	Changeover time (Maximum time)	Joining pressure build-up time	Cooling time under joining pressure (minimum values) p = 0,15 N/mm^2 ± 0,01
mm	mm	s	s	s	min
up to 4,5	0,5	up to 45	5	5	6
4,5 ... 7	1,0	45 ... 70	5 ... 6	5 ... 6	6 ... 10
7 ... 12	1,5	70 ... 120	6 ... 8	6 ... 8	10 ... 16
12 ... 19	2,0	120 ... 190	8 ... 10	8 ... 11	16 ... 24
19 ... 26	2,5	190 ... 260	10 ... 12	11 ... 14	24 ... 32
26 ... 37	3,0	260 ... 370	12 ... 16	14 ... 19	32 ... 45
37 ... 50	3,5	370 ... 500	16 ... 20	19 ... 25	45 ... 60
50 ... 70	4,0	500 ... 700	20 ... 25	25 ... 35	60 ... 80

The information regarding the bead height, the heating-up time, changeover time, joining pressure build-up time and cooling time can be found from the parameter table (see Figure 4). The parameters differ according to the wall thickness. (Lauri, 2015)

Admor Composites uses this technique to weld composite sheets of various length and width of maximum 5 m to get a single unit of desired sheet.

3 DESIGN PROCESS

The design of a product starts after we feel the need for a product in the market or sometimes come with a new idea. New products are also designed to overcome the problems in the existing design. All these design steps start with design requirements. The end for a design process must provide the full specifications of a product, which satisfies most of the design requirements. There are three steps in between the design requirement and the final product specifications: concept, embodiment and detailed design. (Ashby, 2011, s. 16)

The design process started when the customer identified the problem in handling large sheets that led to a need of automated composite sheet welding process. Since the size and weight of the sheets to be weld is very large, it is difficult to handle them manually by individuals, as they must go through different processes. The process includes:

- Feeding sheets into the welding machine
- De-beading the welding seam once it is cooled enough
- Leveling out the edges
- Cutting the welded sheets to get desired size (if needed)
- Stacking the finished product

New problems need innovative solutions along with manipulation of technologies and products already available. This project is a combination of redesigning the manual mechanism with the help of new and existing products and introducing automation.

My concept design includes a use of existing product, modification of available machines and designing one according to the need. Therefore, I started with a market research for the products I need, their availability, modification ability and cost. This report includes detailed information on the market research, concept design, cost calculation and in-factory setup for the whole process.

4 FEASIBILITY STUDY

Automation has become an essential part of industries and businesses now. Automated industries are even aiming for lights off production; a production plant completely automated which needs no human to process the tasks. Many sheet fabrication industries like composite sheet, sheet metal, plywood and plate glass are being involved in automation as well. There are many sheet transfer-based automation solutions available in industrial scale right now.

The design process for this automated platform has multiple constrains. Due to limited area of the warehouse, the platform should take as small space as possible. To cut down initial investment the components used should be able to carry out various tasks in the same facility. Safety is always one of the crucial requirements in any design. However, ergonomic design, reliability and low cost are the main requirements for this design.

4.1 **Market Research**

Sheet fabrication industries usually use either conveyor system or vacuum lifting system for handling large sheets in their automated facilities. Sheets that require less care like plywood use conveyor system whereas delicate materials like glass sheets, sheet metals and composite sheets use vacuum lifting system as it ensures efficient material flow. Figure 5 shows a chain conveyor at a plywood plant in Punkaharju.

Figure 4. A chain conveyor at a plywood plant (Ferroplan, n.d.)

A vacuum lifting system creates a vacuum between the surface of a sheet and a suction cup, which holds the sheet and transport it anywhere as desired. The flexible property of polymer cup and modular frame design allows working with various materials, geometries and surface qualities. Many companies supply automation solutions to industries according to the individual need of customer. The figure below shows a lifting device with overhead crane.

Figure 5. A vacuum lifting device for handling large work piece (Schmalz, n.d.)

Companies like Schmalz offers a wide range of vacuum solutions for handling plastics. Specially developed high-temperature-resistant materials allow handling leaving few marks even when work pieces are still hot, while extremely compact vacuum generators provide maximum dynamics and process reliability. Vacuum lifting is an ergonomics and efficienct solution in manual loading of machining tools. (Schmalz, n.d.)

4.2 Customer needs

Composite sheets of different size and thickness are butt weld together using a plastic sheet butt-fusion welding machine in the factory. Since the maximum width of the sheets are 5 meters, feeding it into the welding machine manually is not only tough but also ineffective. The figure 6 shows a welding operator feeding a composite sheet manually into the welding machine.

Figure 6. Manually feeding sheet into a welding machine

There are commercially available CNC feeding solutions for such operations but a large sheet like this with limited space in the warehouse requires special platform. The facility should also include an automatic edge trimmer and a splitter that makes the whole process more effective and thus, increases manufacturing.

5 PROPOSED IDEAS

There are various automated facilities available for factories and warehouses these days especially when it comes to handling large work pieces. However, every factory needs to have a different approach to automation to get the most out of it because of the uniqueness of their problems and constrictions. The warehouse at Admor Composites Oy has limited space so the automated platform should be as compact as possible leaving enough room for workers to work comfortably.

I came up with two different ideas of using either a chain conveyor system or a vacuum lifter with an overhead crane. Both solutions were presented as a possible solution fulfilling the given design requirements. They have their own pros and cons, so I compared both ideas to find out the best solution in table 2.

Table 2. Ideas Comparison

Chain Conveyor	Vacuum lifter
Simple and economical set up.	Challenging and expensive to set up as it has many components.
Not useful for any other purposes.	Equipped with overhead crane, which can be used for other lifting purposes.
Takes more space.	Takes less space.
No standard models available but possible to customize for wide work piece	Standard models available for any given work piece
Needs to be closely placed to the welding, cutting and stacking station making it difficult to reach for repair and inspection.	Gives enough space for maintenance and inspection
Handling small sheets will be tricky because of the wide gap between conveyor rows.	Modular frame design with movable suction cups make it suitable for smaller work pieces.
Economical	Slightly costly

Based on the comparison above, vacuum lifter meets the required design parameters. Even though it is slightly costly than chain conveyor, it will yield more profit for the company in a long run. So, I concluded to continue to design the platform using a vacuum lifter with an overhead crane.

5.1 Operational sequence

The full operation works on a sequential flow as shown in the figure below. First, the raw sheets will be stacked on a table before the welding machine. The welding operator feeds those sheets into the welding machine. Once the work pieces are in place, the welding machine performs welding automatically. Depending on the wall thickness of the sheets, they are heated from 200°C to 220°C, pressed against each other for 5 to 8 seconds and left to cool down for 6 to 10 minutes. On average, only the welding operation takes about 10 minutes.

When the welded sheets drop to room temperature, it is ready to cut out the welding seam, trim the edges and split the sheet if needed. After obtaining the desired sheet dimension, it is ready for further operation to make a transportation tank.

5.2 Working stations

The operations mentioned above are performed manually except the welding. The use of vacuum lifter will take the production process to a certain level of automation, reducing the number of worker and cutting down the amount of physical stress on the operator. A new cutting machine, which can perform all cutting operation automatically, will accelerate the production process and yield a larger output. I decided to break down the whole process into four different workstations where each station will perform a unique task as shown in figure 7.

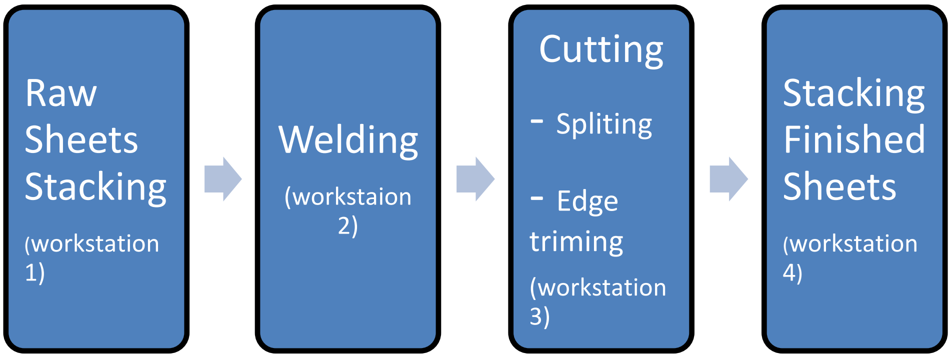


Figure 7. Process flow chart

Frist, sheets at station 1 are fed into the welding machine at station 2 with the help of a vacuum lifter. The welding is performed at station 2 and once the welded sheets are cooled enough, it is then fed into the cutting machine at station 3. Cutting tasks like splitting and levelling the edge is done automatically at station 3. Finally, a single unit of composite sheet of desired size is stacked at station 4 with the help of a vacuum lifter.

6 FINAL DESIGN

6.1 Vacuum Lifter

There are wide varieties of vacuum lifter manufacturers and distributors in Europe with their unique innovative technology and lifting solutions. After a careful evaluation of the current market, I found that VacuMaster Comfort 500 from Schmalz Oy is the best commercially available standard model for this platform. They also have a manufacturer in Finland, so it is easier to buy, low shipping cost, time, and possible for the company’s personnel to visit the factory for initial setup and maintenance.

The vacuum lifter was chosen according to the nature of the work piece: dimension and weight. The maximum work piece to be weld is 1500mm x 5000mm x 4mm (L*B*H) and minimum is 300mm x 300mm x 2mm. When welded together the largest dimension of a single unit would be 5000mm x 3000mm x 4mm with the maximum weight of 300 kg. I also contacted a sales engineer from Schmalz to get the required technical information about the device and address our need. After couple of emails, we figured VacuMaster Comfort with 90-degree swivelling tool, maximum load capacity of 500 kg and standard model gripper is the best solution. The gripper comes with eight suction cups and shut-off valve, which can be turned off for handling smaller work pieces. The swivelling tool helps to rotate the work piece, which is ideal for material handling jobs. Vacuum pump EVE, an electric vacuum generates smooth and suction-tight workpieces. Figure 8 shows a VacuMaster Comfort with 90° swivelling tool.

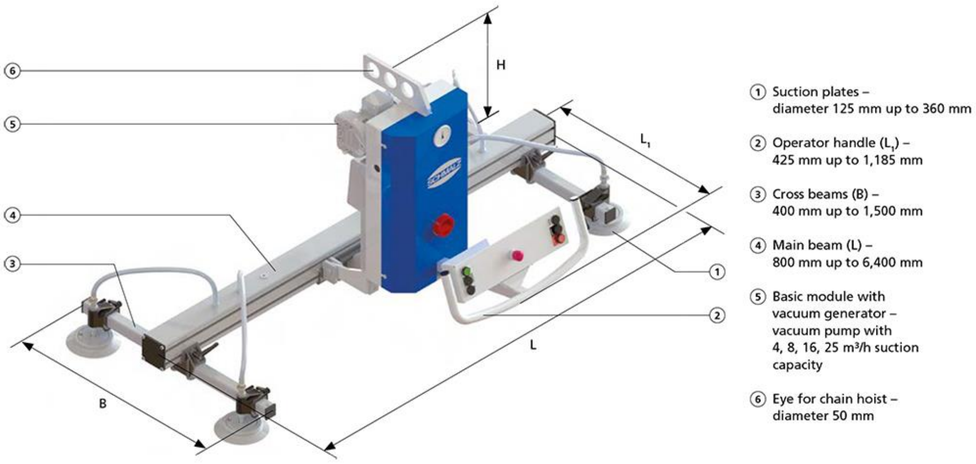


Figure 8. VacuMaster Comfort with a 90° Swivelling Tool (Schmalz, n.d.)

6.1.1 Modular System

One of the reasons to choose VacuMaster comfort is because of its modular property. Connectors, load beam and suction plates help form a light, robust and flexible modular system versatile for every task. The combination of aluminium and high-strength plastic allows the crossbeams and suction plates to be easily adjusted to quickly adapt to changing formats. The large vacuum reservoir prevents the load from falling in the case of a power failure and makes gripping faster during repeated lifting processes. (Schmalz, n.d.)
Figure 9 shows connectors, load beam and suction plates.

Figure 9. Connectors, a load beam and suction plates (Schmalz, n.d.)

6.1.2 Technical Data

Table 3 shows the technical data of VacuMaster Comfort with different dimensions and load capacities. We can see from Figure 11 that increasing the length of load beams by two times and adding the number of suction plates can increase the area of work piece by 60%.

Table 3. Technical Data of VacuMaster Comfort series (Schmalz, n.d.)

Type Max. lift capacity [kg]	Workpiece format [mm]	Dimensions L x B (width) [mm]	Overall height H Basic [mm]	Overall height H Comfort [mm]	Operator handle L_1 [mm]	Suction plates** No.	Suction plates** Ø [mm]	Weight Basic [kg]	Weight Comfort [kg]
Basic / Comfort 125	2,000 x 1,000	1,600 x 750	720	720	725	2	360	74	76
	2,500 x 1,250	1,600 x 750	800	800	725	4	210	79	81
	4,000 x 2,000	3,200 x 1,500	800	800	1,025	8	210	94	101
Basic / Comfort 250	2,500 x 1,250	1,600 x 750	800	800	725	4	260	91	93
	4,000 x 2,000	3,200 x 1,500	800	800	1,025	8	210	102	104
Basic / Comfort 500	2,500 x 1,250	1,600 x 750	1,030	1,030	785	4	360	135	137
	4,000 x 2,000	3,200 x 1,500	1,030	1,030	1.085	8	360	151	153

*The shown VacuMaster are example configurations: The VacuMaster Basic/Comfort can be adapted flexibly to individual workpiece formats.
**The indicated number of suction plates is possible for handling of rigid goods. For unstable and thin workpieces the numbers of suction plates will be increased.

6.2 **Cutting Machine**

A 3-axis CNC router of workspace 5x3 meters was designed to split and trim the edges of the welded sheets at station 3. Figure 12 shows an orthographic view of the final model.

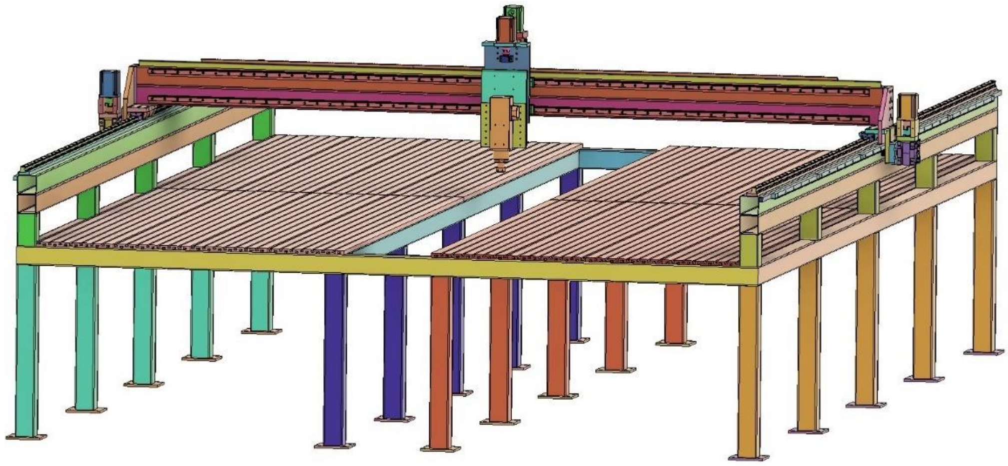


Figure 10. Cutting machine

7 DESIGN DETAILS

7.1 **Beam Selection**

The main components of this design were structural steel beams. While selecting cross section of the beams, we considered the X-axis to be the most critical part of the frame as it is the longest beam in this design with two fixed ends. The deflections are different along the entire length of the beam, but it is maximum in the midpoint. Figure 11 shows a free body diagram of a beam fixed at both ends.

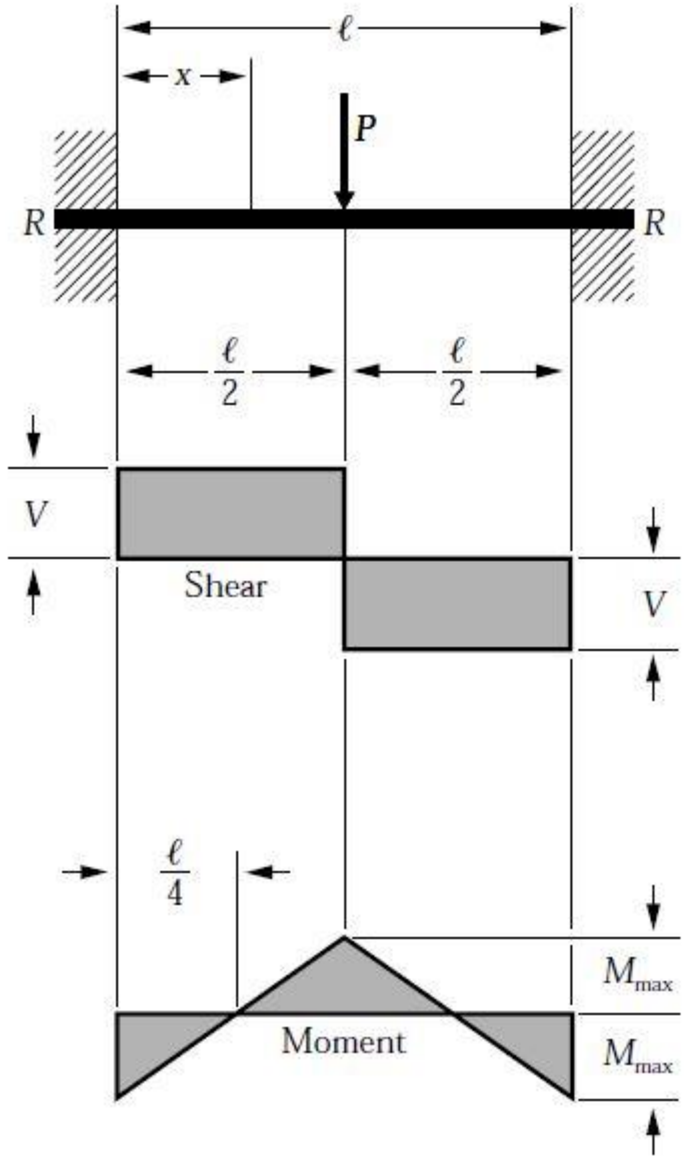


Figure 11. Free body diagram for X-axis (American Forest & Paper Association, Inc., 2007)

The maximum allowable deflection was considered 2mm at the centre. Approaching it by hit and trail method; we first took a square profile of 90x90x3 according to the standard DIN EN10219-2. Mechanical properties of the beam selected are as follows:

Width (B) = 90mm
Specified thickness (T) = 3mm
Mass per unit length (M) = 8.01 kg/m
Cross-sectional area (A) = 10.2 cm^2
Second moment of area (I) = 127cm^4

By using the following formula for maximum deflection at the centre, we got the maximum allowable force to bend the beam by 2mm.

$$\Delta_{\max}(at\ centre) = \frac{Pl^3}{192EI} \quad (1)$$

From equation (1), we are given:
Δ_{max} = 2mm
Total length of the beam (l) = 3519mm
Second moment of area (I) = $127*10^4$ mm^4
Modulus of elasticity of steel (E) = 210,000 N/mm^2

On solving equation (1), we got the force value (P) of 2.4kN. The total weight acting on X-axis is the weight of the beam itself and Z-axis, which gives us a total mass of 220 kg. A total of 2.1kN force acting downwards. Hence, the profile 90x90x3 is strong enough to withstand the possible load.

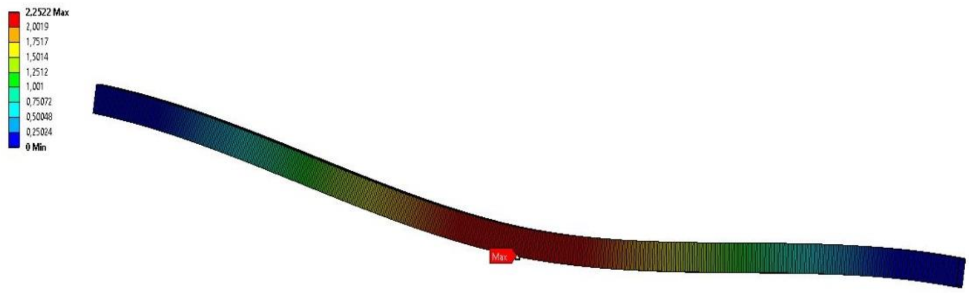


Figure 12. ANSYS analysis for deflection of a single beam fixed at both ends

Furthermore, analysis tool ANSYS was used to check the maximum deflection on the beam while applying a load of 2.4kN at the centre and the results were close to hand calculation values. Following figure shows the deflection while fixed at both ends, blue to red colour indicates minimum to maximum deflection.

As we can see in figure 12, the maximum deflection is 2.25mm, which is slightly more than the allowable deflection value. Therefore, we decided to stack up the beam and after further analysis, we found out that, the deflection was reduced by more than four times. In addition, stacking the beams give enough room to attach Z-axis to X-axis. Figures 15 and 16 show deflection of stacked beams fixed on both ends.

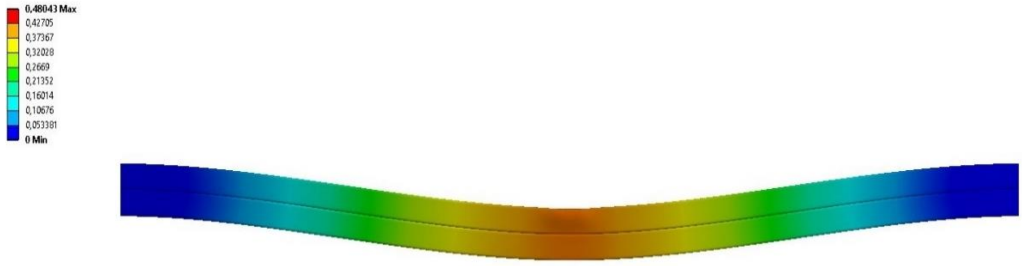


Figure 13. ANSYS analysis for deflection of stacked beams fixed at both ends

On figure 13, we can see that the maximum deflection indicated by red colour is 0.480mm.
A shell analysis of the stacked beam was performed to ensure that the results are correct. Figure 14 shows a shell analysis of the stacked beams

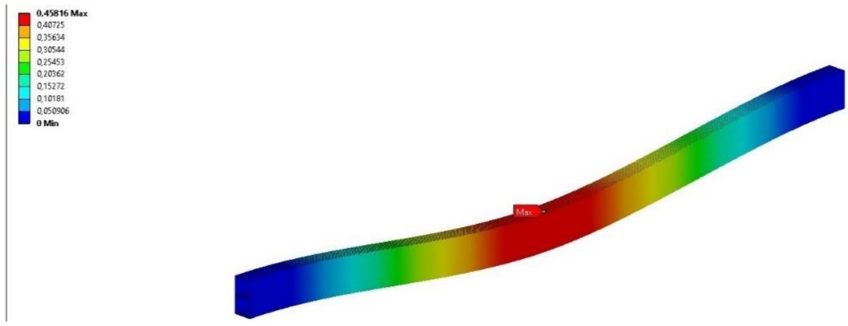


Figure 14. Shell analysis of stacked beam in ANSYS

Here the maximum deflection is 0.458mm, which is very close to the value we got from figure 13. It also means that with the concentrated load value of 2.4kN applied at the center of the beam gives a safety value of 4. Hence, we can conclude that a stacked structural steel beam of 90x90x3 can withstand the desired load generating a very small deflection.

7.2 **Base Frame**

The base frame is a sturdy structure made by using beams of different lengths. All the beams that are used are hollow square structural steel beam of dimension 90x90x3. The overall length, breadth and height of the frame is 5500x3500x1214 mm that gives a working space of 5000x3000 mm. The working space is at the height of 890 mm from the ground. The base plates are made of 160x160x10 mm structural steel with four holes on each corner to attach it to the ground with M14 bolts. All the beams are welded together making it a stable frame with high load carrying capacity. The gap of 422 mm on the X-axis of the frame allows the cutting tool to split any work piece larger than 500 mm. Figure 15 shows a projected view of the frame with some peripheral dimensions.

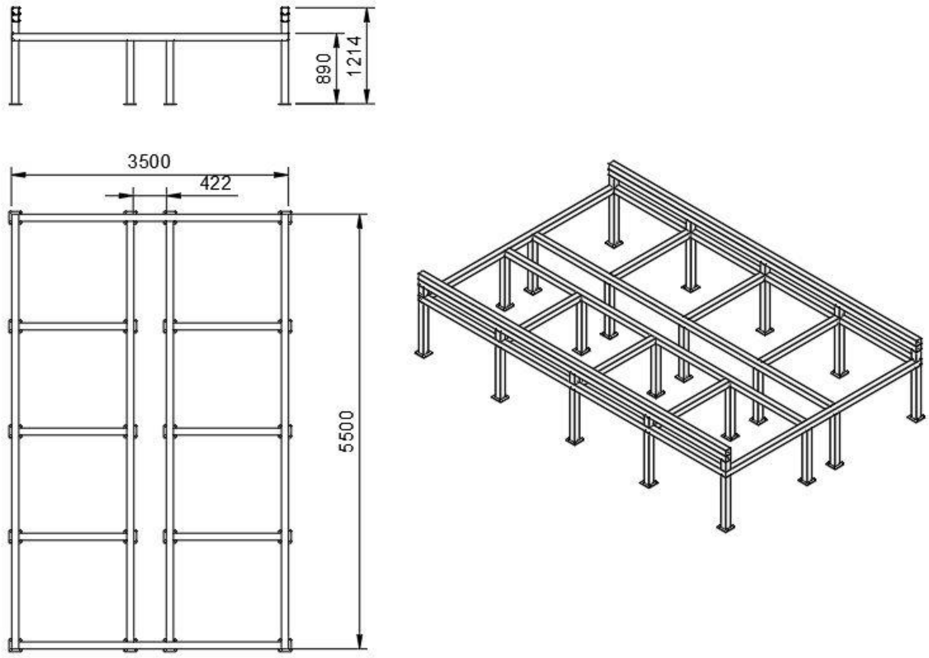


Figure 15. Base Frame of the CNC router

7.3 **Y-axis**

The Y-axis is made of two 90x90x3 beams stacked on top of each other with a total length of 5500 mm. It consists of a Thomson linear bearing profile rail with two carriages, an R&P anti backlash module with Worm Gearbox v40 1:10 gear reduction ratio by Damen CNC, module 2.0 rack and pinion rail by Damen CNC, NEMA 34 stepper motor, a bearing mount and a sidewall mount. Figure 16 shows a 3D view of Y-axis with its components. It is the longest side of the machine and can operate through 5000 mm. Rack and pinion drive type system are used to make the linear motion possible along this axis.

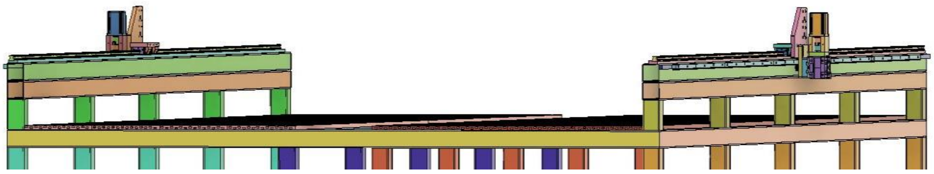


Figure 16. Y-axis

7.4 **X axis**

Like Y axis, the X axis is also made of two 90x90x3 beams stacked on top of each other with a total length of 3519 mm and an effective operating distance of 3000 mm. It also houses Z-axis in this CNC router. It is the longest part in the machine with no support but only two fixed ends. The Z-axis runs along X-axis with the help of rack and pinion drive type system. For linear motion, it consists of Gudel Sumer 1:10 NR100 planetary gearbox with an output pinion, NEMA 34 stepper motor, and a module 3 Gudel Sumer helical rack. Figure 19 shows a 3D view of X-axis and its components.

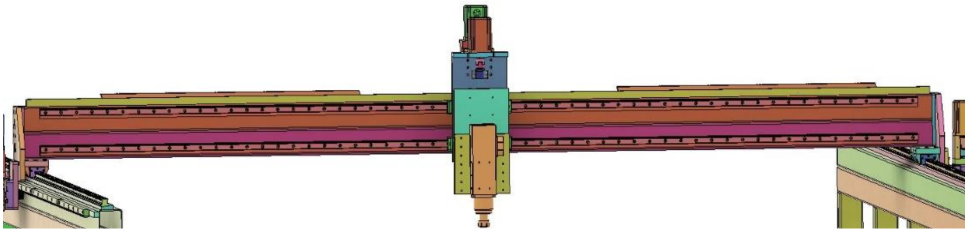


Figure 17. X-axis

7.5 **Z axis**

Unlike X and Y-axes, the Z axis is oriented vertically and allows the cutting tool to move up and down along the plane. RM1605 ball screw powered by NEMA 34 stepper motor is used for vertical motion of this axis. It can cover a vertical distance of 250 mm. A proximity sensor placed on the top plate of the Z-axis determines the zero position for the front plate and measures the distance of its movement. It has a spindle mount attached to the front plate, which holds a TeknoMotor C41/47 spindle. The spindle mount makes it easier to change the spindle if needed. Manual tool changing is possible with just an Allen key. Figure 18 shows a projected view of Z-axis.

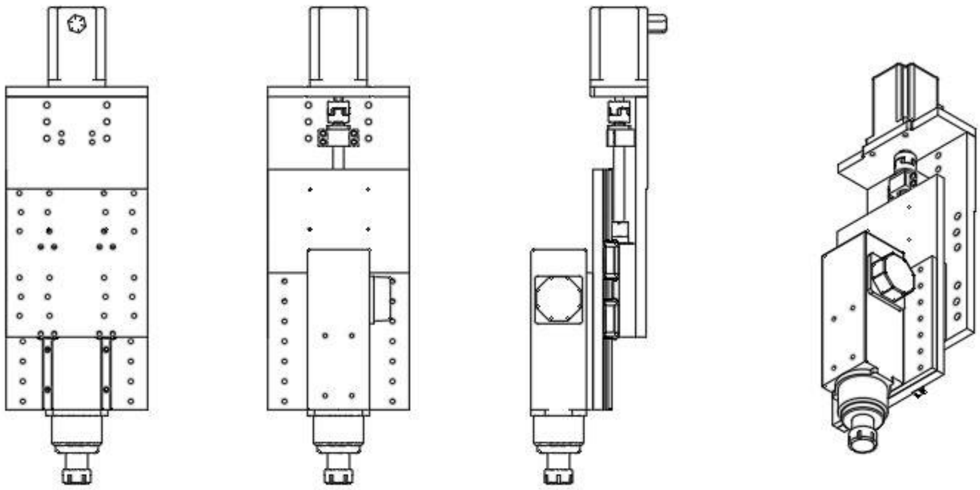


Figure 18. Z-axis

7.6 **Rack and Pinion Drive System**

A rack and pinion drive system consist of a rack (or a “linear gear”) and a pinion (or “circular gear”). The teeth of a rack and pinion drive can be straight or helical, although helical teeth are often used due to their higher load capacity and quieter operation. For a rack and pinion drive system, the maximum force that can be transmitted is largely determined by the tooth pitch and the size of the pinion. (MotionControlTips, 2019)

This system is used as a linear drive mechanism for motion in X and Y axes because of its extremely long length. In Y-axis, it is spread over the length of 5500 mm while in X-axis it covers a length of 3500 mm, giving us a working area of 5000x3000 mm.

The rack and pinion system in Y-axis consist of following elements:

- Worm Gearbox v40 1:10 gear reduction ratio by Damen CNC
- Zero Backlash Coupler
- module 2.0 rack rail by Damen CNC
- NEMA 34 stepper motor

Figure 19 shows a complete rack and pinion drive module with mounting plates and a NEMA 34 stepper motor.

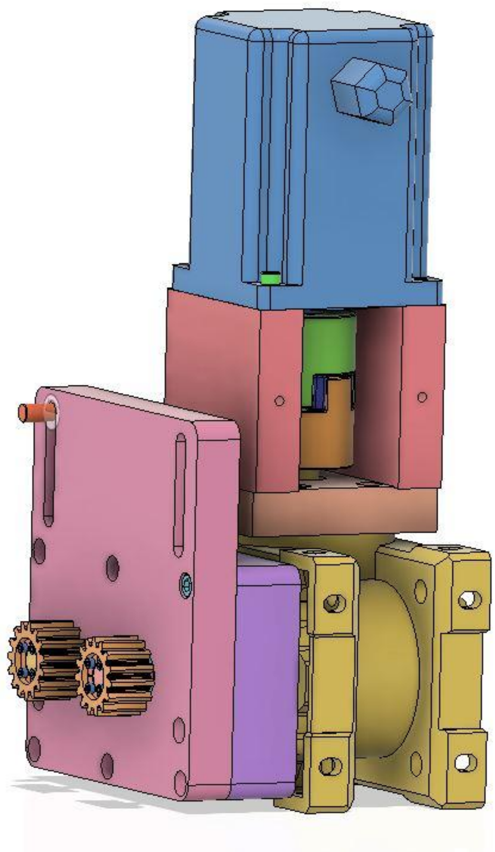


Figure 19. R&P Drive Module CAD model

The following calculation shows how many steps the stepper motor needs to cover 1 mm.

Step angle = 200 steps/revolution (1.8 degrees)
Stepper motor driver setting (say) = 16 micro steps
Multiplying it gives us 3200 steps/ revolution, which means the stepper motor must make 3200 steps to make a full revolution. The stepper motor is connected to a Worm Gearbox with a reduction ratio of 1:10, which means for each revolution the pinion must rotate, the stepper has to rotate 10 revolution.
That implies that we need 32000 steps to rotate the pinion gear by one revolution.
The pinion has 15 teeth at mod 2.
We have:
Travel distance = mod*π*teeth
= 2*3.14159*15
= 94.2477 mm
This means that for every revolution the pinion makes it has a linear travel distance of 94.2477 mm.
If 32,000 steps in the stepper motor makes a linear travel distance of 94.2477mm, then to travel a linear distance of 1 mm in the Y-axis, the stepper motor needs 339.5 steps.

The rack and pinion system in the X-axis are slightly different and consists of the following elements:

- Gudel Sumer Planetary gearbox NR 100 1:10
- Module 3 helical rack
- NEMA 34 stepper motor

Figure 20 shows a Gudel Sumer planetary gearbox with a NEMA 34 stepper motor.

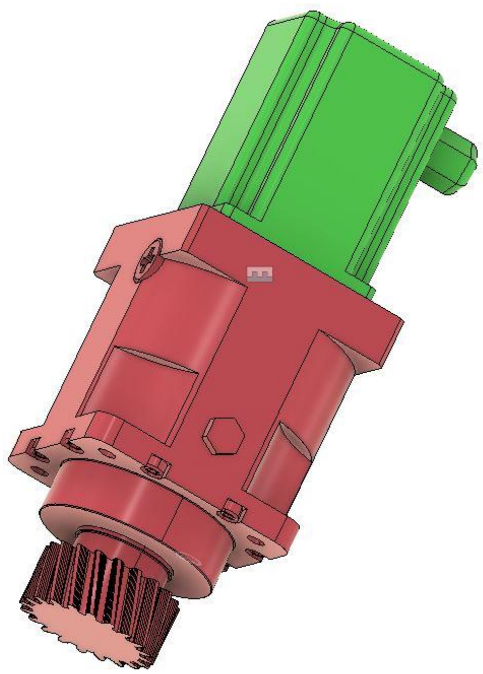


Figure 20. Gudel Sumer Planetary Gearbox CAD model

The following calculation shows how many steps the stepper motor needs to cover 1 mm in X-axis:
Step angle = 200 steps/revolution (1.8 degrees)
Stepper motor driver setting (say) = 16 micro steps
Multiplying it gives us 3200 steps/ revolution, which means the stepper motor must make 3200 steps to make a full revolution. The stepper motor is connected to a Planetary Gearbox with a reduction ratio of 1:10, which means for each revolution the pinion must rotate, the stepper has to rotate 10 revolution.
That implies that we need 32000 steps to rotate the pinion gear by one revolution.
The pinion has 20 teeth at mod 3.
We have,

$$\begin{aligned} \text{Travel distance} &= \text{mod}*\pi*\text{teeth} \\ &= 3*3.14159*20 \\ &= 188.5 \text{ mm} \end{aligned}$$

This means for every revolution the pinion makes it has a linear travel distance of 188.5 mm.
If 32,000 steps in the stepper motor makes a linear travel distance of 188.5 mm, then to travel a linear distance of 1 mm in X-axis, the stepper motor needs 169.7 steps.

7.7 **Clamping Solution**

A clamping system must hold the work piece firmly against the locating elements and the cutting forces developed during operation without causing damage to it. Clamping device should be incorporated into the jig or fixture, proper clamping in a fixture directly influence the accuracy and quality of the work done and production cycle time. (Rane, 2016)

Our work pieces were made of non-ferromagnetic materials, flexible and because of their extremely large size and flat surface, they were difficult to be clamped mechanically and without distortion. A vacuum clamp is the most effective solution to a problem like this. The advantages of using vacuum clamps to this project were as follows:

- Easy and short setup time
- No risk of distortion
- Modular design of vacuum plates helps to clamp work pieces of virtually any size
- Excellent precision
- High holding force
- Vacuum plates can be secured quickly on t-slot machine table with clamping claws

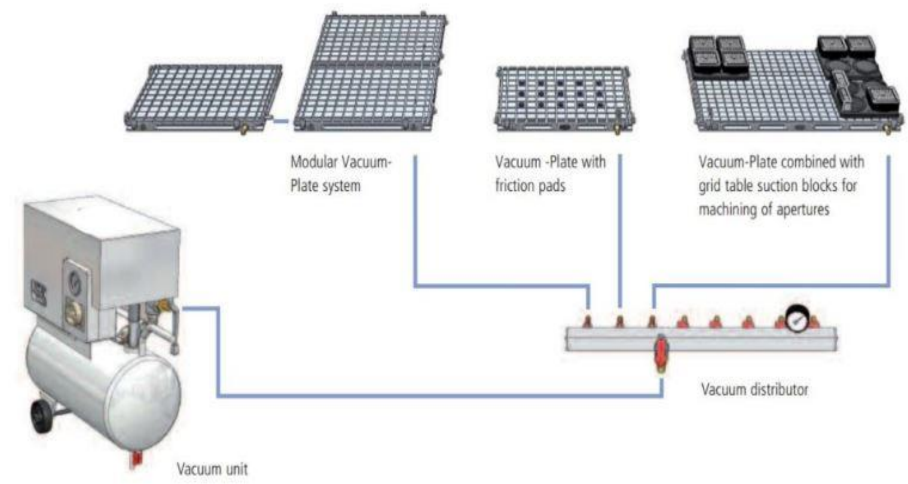
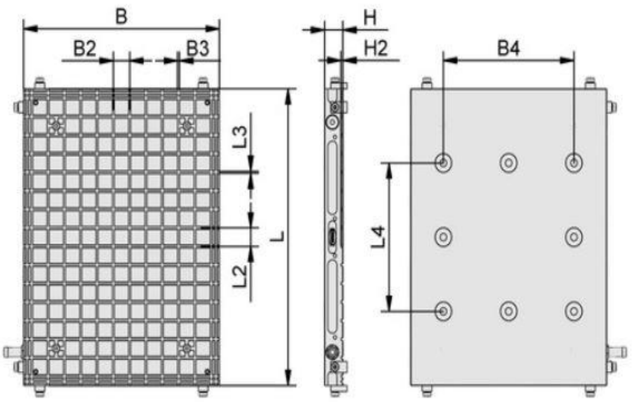


Figure 21. Flexible layout of a complete vacuum clamping system (Spreitzer, n.d.)

Clamping solutions provided by Schmalz were well suited to our needs because of their modular clamping system equipped with vacuum blocks. The required clamping area can be increased as needed by combining several matrix plates. All plates with the same groove size can be connected with each other on all four sides, enabling even large work pieces to be clamped with ease. Vacuum blocks are positioned flexibly above the vacuum openings and are magnetically prefixed which allowed us to trim the edges of the work pieces without any hindrance. A vacuum plate called Matrix-Plate MPL 600x400x28 by Schmalz with 25x25 mm grid and 3x3 mm slot was placed modularly across the machine table. The vacuum plate was used primarily to the clamp the work piece for splitting purposes. Figure 22 shows design data of an MPL 600x400x28 vacuum plate.



Attribute	Value
B	400 mm
B1	430 mm
B2	22 mm
B3	3 mm
H	28 mm
H1	36.5 mm
L	600 mm
L1	625 mm

Figure 22. Design data of vacuum plate MPL 600x400x28 (Schmalz, n.d.)

The required clamping force can be calculated as follows:
A vacuum suction area of 100 x 100 mm results in a theoretical suction area of 10,000 mm². With a system vacuum of -0.8 bar (= 0.08 N/mm²), the formula

$$p = \frac{F}{A} \rightarrow F = p * A$$

results in a theoretical normal force or suction force of:

$$F_N = 0.08 \, \frac{N}{mm^2} * 10000mm^2$$

$$F_N = 800N$$

The horizontal friction force is defined using the formula

$$F_R = \mu * F_N$$

Using an adopted value of μ = 0.1 and the normal force above results in a friction force of

$$F_R = 0.1 * 800N = 80N$$

For trimming the edges of our work pieces, we needed a small gap to run a milling tool between the work piece and the vacuum plate. Another product by Schmalz called Innospann Steel-Plate System (ISST-MPL) used along with Innospann vacuum block (ISBL) provides that gap to trim the edges securely and without any disturbance. An Innospann Steel Plate (ISST-MPL) of size 600x400x3 mm was placed on top of the vacuum plate, which housed an 80x80x97 mm vacuum block giving us a height clearance of 97 mm between the work piece and the clamp. Figure 23 shows a combined use of a vacuum plate (MPL), ISST-MPL and ISBL for milling purposes.

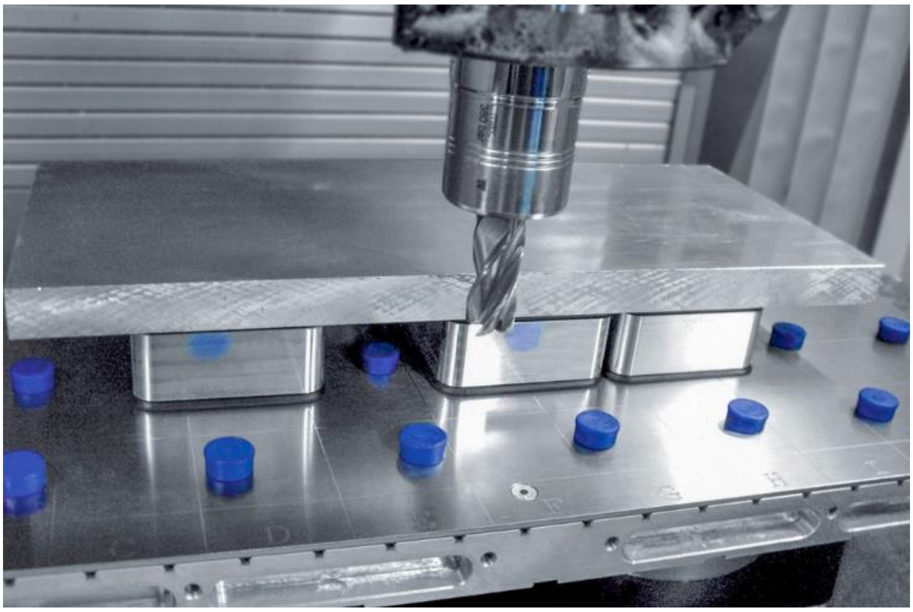


Figure 23. Milling using vacuum clamping technology (Schmalz, n.d.)

8 SAFETY AND MAINTENANCE

Work safety and the reliability of a system are the primary concerns in every mechanical design. Handling large work pieces can be hazardous if enough safety measures are not considered. Fully trained and authorized personnel should only operate the platform.

For applications where many hands would normally be required, the VacuMaster allows work pieces to be handled effortlessly by just a single operator while protecting the employee’s health. The electronic warning device ensures safety: it warns the employee in time in the event of a drop-in pressure. Operator should always be aware of specific hazards like danger of power outage, pump failure, line breaks or sudden leakage. (Schmalz, n.d.)

While using the matrix plate for clamping, the operator must ensure the following safety measures:

- The matrix plate must only be used as intended (designated use).
- The matrix plate must only be used as intended (designated use).
- The operating instructions must be kept in a legible and complete condition and must always be available where the machine is in operation.
- The operator must be trained regularly in all aspects of work safety and environmental protection and must be familiar with the operating instructions. (Schmalz, n.d.)

Safety tips for using the CNC router:

- Prepare and review the program carefully.
- Always wear safety gears like gloves, safety shoes and glasses while operating or inspecting the machine.
- Keep a safe distance from the machine when it is running.
- Do not force any material into the router.
- Make sure the clamping force is enough and the work piece is clamped down properly before operating.
- If the tools breaks, shut down the machine immediately.

The most delicate part in the CNC router is the rack and pinion drive and it needs regular monitoring and maintenance. The rack and pinion are susceptible to damages generally seen on gears. Rack and pinion set last longest when properly regulated but the relative movements of the gears and abrasive particles in the lubricant can cause material loss. Dust or chips from the production environment and the process can contaminate the system.

9 RESULTS AND CONCLUSION

The concept of an automated platform introduced in this thesis met all the requirements set by the customer. The most important achievements of this design were to reduce the number of workers to one and to cut down physical stress on the welding operator while fitting all units within a definite space. Most of the parts used in building this platform were available in the Finnish market. Production processes like cutting, drilling, welding and machining were used to build most of the CNC router, which made it less expensive to construct.

In conclusion, this thesis provided the company an optimal solution to automate the welding process increasing their productivity. It guided me to grow as a machine designer and a product developer. This project helped to boost my skills in 3D modelling, strength calculations, market research and report writing.

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