

# Design of a Support System for a Re-configured Milling Machine to Achieve Friction Stir Welds

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**Abstract— The detailed design of a clamping and support system for a reconfigured milling machine to produce friction stir welds is reported in this paper. Two different concepts were considered and subjected to performance evaluation. The selected design concept is expected to effectively clamp and support the workpiece during the process of friction stir welding to achieve a good integrity.**

**Keywords—Clamping, Friction Stir Welding, Reconfiguration, Support systems.**

## I. INTRODUCTION

FRICITION Stir Welding (FSW) is a solid-state joining technique invented and patented by The Welding Institute (TWI) in 1991 for butt and lap welding of ferrous and non-ferrous metals and plastics [1]. Since its invention, the process has been continually improved and its scope of application expanded. The novelty of this welding procedure is due to the fact that unlike conventional welding, it does not create brittle bonds caused by the localized heating of metal or Heat Affected Zone (HAZ). The localized heating present in conventional welding alters the chemical composition within that heated section. This severely alters the mechanical properties of the metal and further heat treatment is required to resolve this shortfall. The major advantage of FSW is that the heat is generated internally via a mechanical method and therefore localized heating does not occur. FSW operates by simultaneously combining heat caused by friction along with pressure to produce resilient bonds which have been known to be of excellent quality.

The specialized machinery for FSW is however extremely costly, making them highly inaccessible. These results in low amounts of continuous research in the field of FSW which negatively affects the ability to better understand the mechanisms behind this welding technology. Due to this, the advancement into FSW technology is slow and much room is available for optimization in this field.

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It has been previously shown that sufficiently powerful enough milling machines are able to produce friction stir welds, given that they are equipped with the correct adaptations [2]. Such milling machines with this required power are commonly found in universities across the world. A modern integrated system is required to conduct FSW using a milling machine. The advantages of FSW completely outweigh that of typical arc or fusion welding. It is therefore deemed necessary to develop a reasonably cost effective and efficient method of adapting typical milling machines in such a way that FSW can be successfully conducted without the requirement of highly specialized and remote machinery.

To effectively design a clamping and support system in a reconfigured milling machine to produce friction stir joints, it is necessary to understand some of the influencing factors. It is important to note that FSW operates by simultaneously combining frictional heat and pressure. The frictional heat generated during this process together with the rotating and traversing of welding tool softens the material at the joint interface and produces plastic flow that effectively stirs the material from the sections of both parent materials and fuses them together to create a weld. The re-designing of a milling to produce friction stir welds is essentially a mechatronic system consisting of both mechanical and electrical components operating together to achieve the goal. The objective of this design is to develop a clamping and support system for a reconfigured milling machine to be utilized for producing friction stir welds. An outstanding feature of this design is its adaptability on almost any milling machine.

## II. PRINCIPLE OF OPERATION OF FRICTION STIR WELDING

The operations during FSW consist of several phases of action; each phase can be described as a time period where the welding tool and the workpiece are moved relative to each other. In the first operation, the tool is plunged vertically into the joint line between the workpieces, while the tool is rotated. This action takes place in the plunge period. The plunge period is followed by the dwell period, where the tool is held steady relative to the workpiece but still rotating. The mechanical interaction, due to the velocity difference between the rotating tool and the stationary work piece, produces heat by frictional work and material deformation. This heat dissipates into the surrounding material, the temperature rises and the material softens. After these two operations, the actual welding process can be initiated by moving either the tool or the workpiece relative to each other, along the joint line. When the desired weld distance is covered, the tool is

retracted from the workpiece leaving behind an exit hole as a footprint of the tool.

The tool consists of a probe or pin extruding from the center of the tool's contacting surface. The probe can be threaded or unthreaded. The probe is responsible for generating a mechanical mixing process in the plasticized material. Only a fraction of the total heat is generated by the probe. The cylindrical surface responsible for generating the frictional heat is known as the shoulder of the tool. A schematic of a simple tool for FSW is shown below in Fig. 1.

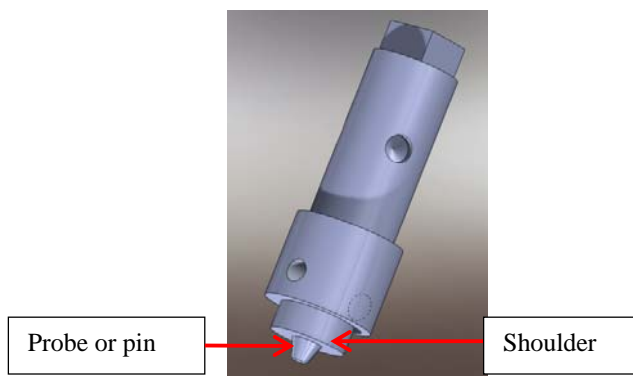


Fig. 1: Simple FSW tool [3]

The shoulder confines the underlying material to avoid wormhole formation and porosity behind the probe. The shoulder is generally concave thus producing a conical shape. The conical tool shoulder helps establish a pressure under the shoulder but also acts as an escape volume for the material displaced by the probe during the plunge action. The phases involved in producing friction stir welds are depicted in Fig. 2.

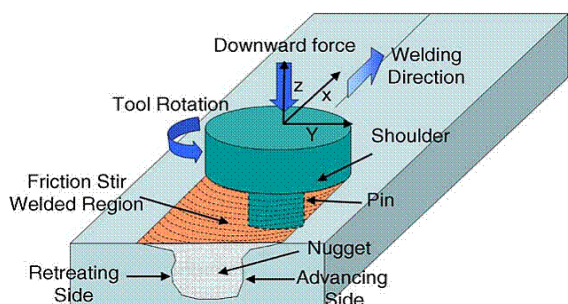


Fig. 2: Schematic diagram of the Friction Stir Welding process [4]

### III. DESIGN CRITERIA

#### A. Product Design Considerations

The Product Design Considerations (PDC) for the redesigned milling machine that will effectively produce a friction stir welds of high quality integrity include the following but not limited to it: Cost effective, energy efficient, minimum maintenance requirement, corrosion resistance, infrastructure designed for simple assembly, materials of construction are chosen for corrosion thermal efficiency and

conforms to statutory requirements. Other factors to be considered also include; occupational Health and Safety Act, aesthetically pleasing, affordable and can be adapted to fit on most milling machines.

#### B. Ranking of the Criteria

The main criteria were selected according to the PDC and these were compared against each other in order to identify the weighting of each of the criteria. This was also used to establish how each of the alternatives performs in different criteria. The different criteria are denoted by  $C_1$ ,  $C_2$ ,  $C_3$ ,  $C_4$  and  $C_5$  respectively and shown below.

- $C_1$  = Safety.
- $C_2$  = Cost Effectiveness.
- $C_3$  = Energy Efficient.
- $C_4$  = Manufacturability.
- $C_5$  = Simplicity.

All these criteria were compared against each other to identify the importance of each as shown in Table I. The weighting is calculated by dividing each of the respective criteria total by the sum of the criteria total. This was effective obtaining the fraction of each criterion with respect to the overall total criteria. As presented in Table 1, the total of the weighting is equal to 1. Therefore the weighting of each criterion are as follow:

$$C_1 = 0.4, C_2 = 0.3, C_3 = 0.1, C_4 = 0.2, \text{ and } C_5 = 0.0$$

TABLE I  
RANKING OF THE CRITERIA

Criteria	$C_1$	$C_2$	$C_3$	$C_4$	$C_5$	Total	Weighting
$C_1$	x	1	1	1	1	4	0.4
$C_2$	0	x	1	1	1	3	0.3
$C_3$	0	0	x	0	1	1	0.1
$C_4$	0	0	1	x	1	2	0.2
$C_5$	0	0	0	0	x	0	0
Total						10	1

As shown, the most important criterion is safety. This is generally the criterion with the highest weighting. Followed by safety in descending order are; cost effectiveness, manufacturability, energy efficiency and lastly, simplicity. No weighting was calculated for simplicity. This is reasonable as the design aims to incorporate mechatronic systems which are able to simulate and analyze the friction stir welding processes without using modernized highly expensive and remote FSW facilities. The major objective of this design is to allow for successful FSW equipment which can be purchased at a relatively low price and be implemented in milling machines. The successful redesign of milling machines to achieve friction stir welds should result in increased studies being conducted in the field of FSW which may allow the industry

to gain further insight into the capabilities and mechanisms of FSW. Together with these criteria weighting, a similar method is used to conduct a simple analysis on selecting the most appropriate concept for the design.

#### IV. CONCEPT GENERATION

From the Product Design Considerations (PDS) several ideas were brainstormed and noted. Consideration was then given to the most viable concepts and a final concept was selected based on the ranking criteria. The design considered in this respect is the clamping and support system for a re-configured milling machine for producing friction stir welds.

The support and clamping system is expected to hold the sample to be welded on the machine bed rigidly with minimum movement during the welding process. This selection firstly addresses various concepts which were generated as proposed alternatives for the clamping and support system, after which the feasibility of each concept was analysed and evaluated. Considering the X-Y table of a typical milling machine, it becomes evident that a backing plate and a clamping system must be designed and implemented on the X-Y table of the milling machine in order to support the workpieces during the process. The backing plate is placed under the workpieces mainly for the protection and the stability of the workpieces. It is also used to avoid splattering and melting of any work piece material on to the X-Y table of the milling machine. A very stable support system is essential as any movement of the workpieces will result in internal voids. Fig. 3 shows a close-up of a typical X-Y table. This close-up allows for the possible concept generation for the design of the backing plate.

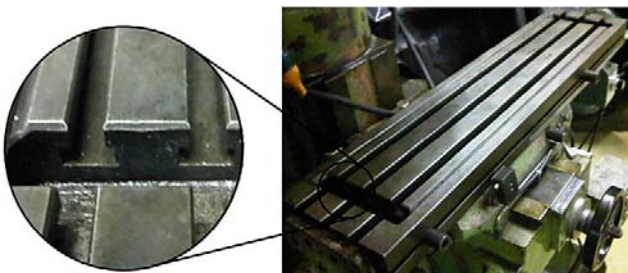


Fig. 3: Typical milling machine X-Y table

##### A. Concept One

A three dimensional view of the backing plate based on concept one is shown in Fig. 4. The assembly drawing illustrating the backing plate, the workpiece and the clamping system mounted onto the X-Y table of the milling machine are shown in Fig. 5.

Also illustrated in Fig. 6 is the cross sectional view showing the mechanism used to fasten the backing plate to the X-Y tables and the mechanisms to fasten the workpiece onto the backing plate. The bolts in the center are tightened to fasten the backing plate to the X-Y table. The bolts on the ends are tightened to fasten the clamps down to the backing plate. By placing the workpieces between the backing plate and the

clamps, a downward force can be applied via the bolts to hold the workpieces firmly against the backing plate to effectively eliminate any movement as well as reduce vibration of the work pieces.

A closer illustration at the mechanisms used to fasten the workpieces together is shown below in Fig. 7. This mechanism allows the weld faces of the two plates to be tightly pressed against each other. This is essential in order to reduce or preferentially eliminate any air gaps between the plates prior to welding as these will influence the formation of internal voids and discontinuities during the welding process.

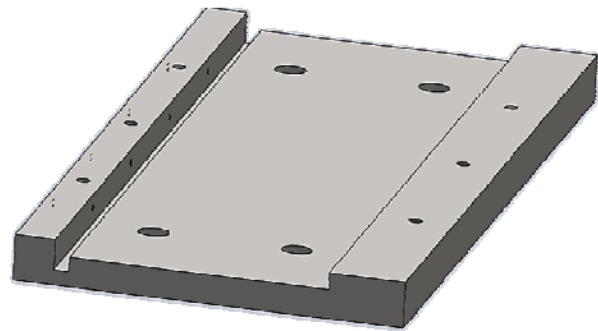


Fig. 4: Backing plate based on concept one.

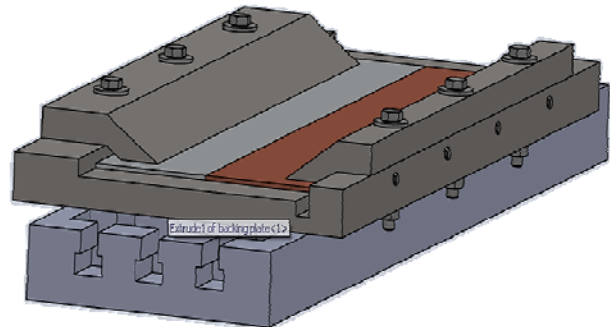


Fig. 5: Assembly drawing of the backing plate, workpiece and clamping system mounted on the X-Y table of a milling machine [5]

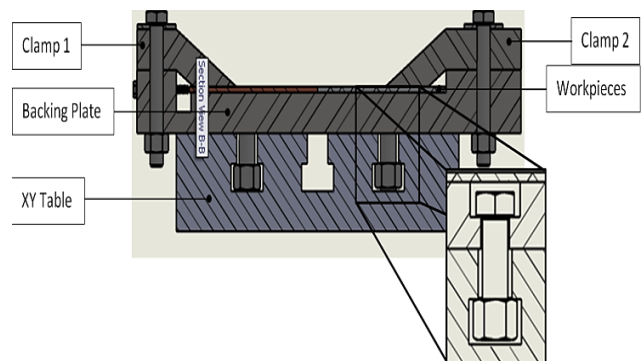


Fig. 6: Cross sectional view of the backing plate, work piece and clamping system



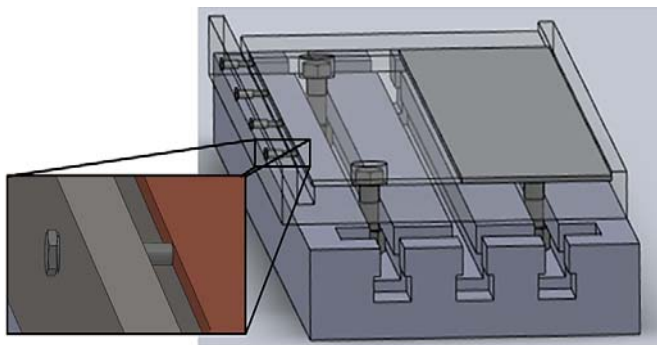


Fig. 7: weld face clamping system

### B. Concept Two

The detailed features of the backing plate based on the second concept are shown in Fig. 8. The complete assembly drawing showing the backing plate fastened to the X-Y table together with the clamping system for the workpieces is displayed in Fig. 9.

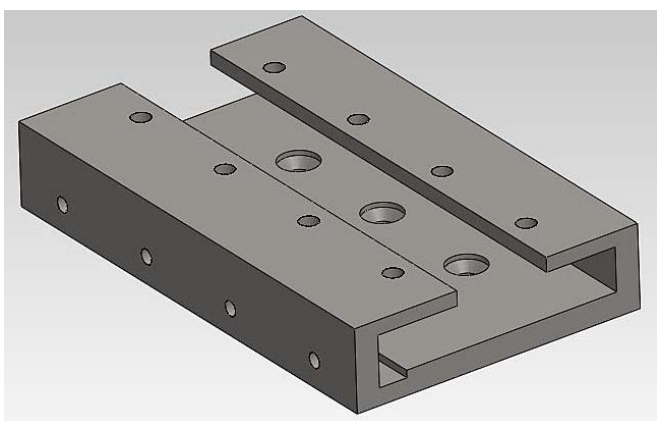


Fig. 8: The backing plate based on concept two

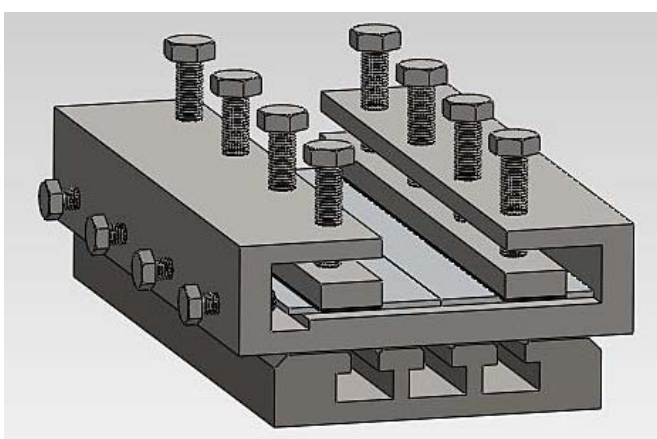


Fig. 9: Assembly drawing showing the backing plate fastened to the XY table of the milling machine and the clamping system

It is important to note that concept two works in a similar manner as the system described for the concept one because bolts were also used to fasten the backing plate to the X-Y table. For the second concept, the clamps are laid on each workpiece and then pressed down against the workpiece using hex bolts which is fastened vertically through the backing plate. The other set of hex bolts were fastened horizontally through the backing plate to allow the workpieces to be pressed against each other firmly.

### V. CONCEPT SELECTION

The merit and demerit of the two concepts were evaluated in order to successfully select the most viable concept. The merit and demerits are presented in Table II and III.

TABLE II  
MERITS AND DEMERITS OF CONCEPT ONE

Merits	Demerits
Simple assembly and disassembly.	Specific design for XY table.
Readily available fastening equipment.	Not easily adjustable for various work piece thicknesses.
Wide area for tool movement.	Vibration not minimized.
No welding procedures required to manufacture backing plate.	Limited work piece width.

It was observed from Table 2 that concept one seems to be a simpler and cheaper design. However, concept two shown in Table 3 provides a stronger clamping and support system with additions to help reduce vibration through the workpieces. The only major concern with concept two was the small area allowed for the tool to traverse. This problem however was easily overcome by first knowing the diameter of the tool which is to be used and then designing the backing plate with this taken into consideration. Not much difference was identified regarding safe use between the two concepts because as both are relatively simple to use and user friendly. As a result of the importance of producing high quality welds with the re-configured milling machine, it is essential to have a very sound clamping and support system. Looking at concept one, it is designed specifically for X-Y table and not easily adjustable, it does not totally eliminate vibration and in addition, the irregular shape of the clamps will require complex machining procedure thus reducing the manufacturability of concept one. On the other hand, concept two is simple but fast clamping assembly; vertical clamping of the workpiece is very effective and above all reduces all form of vibration to a minimum during the welding process.

TABLE III  
MERITS AND DEMERITS OF CONCEPT TWO

Merits	Demerits
Easy installation of backing plate and clamps.	Complex manufacturability for backing plate.
Vibration reducing clamps.	Specialized material and assembly for construction of clamps.
Sturdy design.	Limited area for tool diameter.
Socket screw allows for greater fastening of backing plate to XY table.	Requires specialized socket screw for fastening to XY table.
Vertical clamping of the work piece very effective.	
Allows for various thickness of work piece without compromising the downward clamping efficiency.	
Simple and fast clamping assembly.	
Greater range of work piece widths.	
Work piece length only limited by milling machine capability.	

With reference to the earlier analysis of the criteria ranking, safety was ranked first among others followed in the descending order are; cost effectiveness, manufacturability, energy efficiency and lastly, simplicity. Together with these criteria weighting a similar method was used to conduct a simple analysis on selecting the most appropriate concept for the design. The alternative designs were compared against each other for each of the criteria to find the best alternative for the design. Each concept was consequently represented by  $A_1$ , and  $A_2$ , respectively, hence:

$A_1$  = Concept One.  
 $A_2$  = Concept Two.

The two designed concepts for the clamping and support system were analysed through the ranking criteria discussed earlier and presented are the outcome for each criteria. Table IV presents the comparison of the concepts against each criterion. The weighting of the criteria used is represented by  $W C_n$ , where n represent the criteria being used.

TABLE IV  
CONCEPT SELECTION ANALYSIS

C1 - Safety					
Concept	$A_1$	$A_2$	Total	$W C_1$	$W C_1 \times$ Total
$A_1$	x	1	1	0.4	0.4
$A_2$	1	x	1	0.4	0.4
C2 - Effectiveness					
Concept	$A_1$	$A_2$	Total	$W C_2$	$W C_2 \times$ Total
$A_1$	x	0	0	0.3	0
$A_2$	1	x	1	0.3	0.3
C3 - Energy Efficiency					
Concept	$A_1$	$A_2$	Total	$W C_3$	$W C_3 \times$ Total
$A_1$	x	1	1	0.1	0.1
$A_2$	1	x	1	0.1	0.1
C4 - Manufacturability					
Concept	$A_1$	$A_2$	Total	$W C_4$	$W C_4 \times$ Total
$A_1$	x	0	0	0.2	0
$A_2$	1	x	1	0.2	0.2
C5 - Simplicity					
Concept	$A_1$	$A_2$	Total	$W C_5$	$W C_5 \times$ Total
$A_1$	x	0	0	0	0
$A_2$	1	x	1	0	0

The concepts' weightings are therefore evaluated to determine the highest total value. The concept with the highest total was regarded as the best concept for the design and the summary is presented in Table V.

TABLE V  
SUMMARY OF DESIGN CONCEPTS

Concept	Criteria $W C_n \times$ Total					Total
	$C_1$	$C_2$	$C_3$	$C_4$	$C_5$	
$A_1$	0.4	0	0.1	0	0	0.5
$A_2$	0.4	0.3	0.1	0.2	0	1

Concept two which has the highest rating was therefore selected for further detailed design in this respect.

## VI. PERFORMANCE SIMULATION AND ANALYSIS

The performance simulation and analysis of the design conducted to test if the mission analysis and product Design Considerations (PDC) have been met by the selected concepts. The analysis of the selected concept for the support system involves the analysis of the mechanisms designed to clamp and support the workpiece when fastened on the X-Y table of the milling machine. Fig. 10 shows the backing plate fastened to the X-Y table of the milling machine.

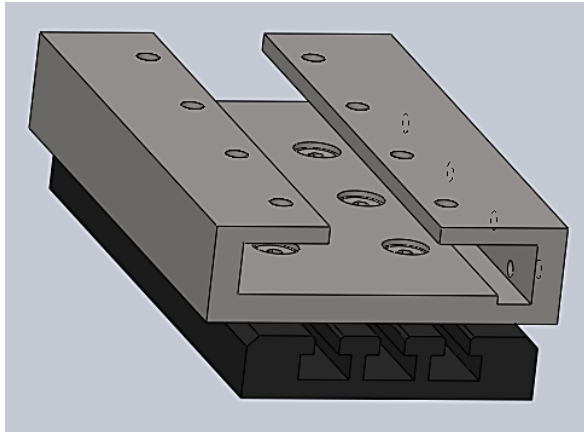


Fig. 10: Backing plate fastened to the XY table

The fastening of the backing plate to the X-Y table was achieved by drilling countersunk holes into the backing plate's workpiece surface which lie directly above the grooves of the X-Y table. The locations of the holes are dependent on the dimensions of the X-Y table and thus each backing plate is uniquely machined to allow for fastening onto its specific X-Y table. This method provides a perfectly unobtrusive mechanism to securely fasten the backing plate to the X-Y table. The sectioned view of the fastened mechanism is shown in Fig. 11.

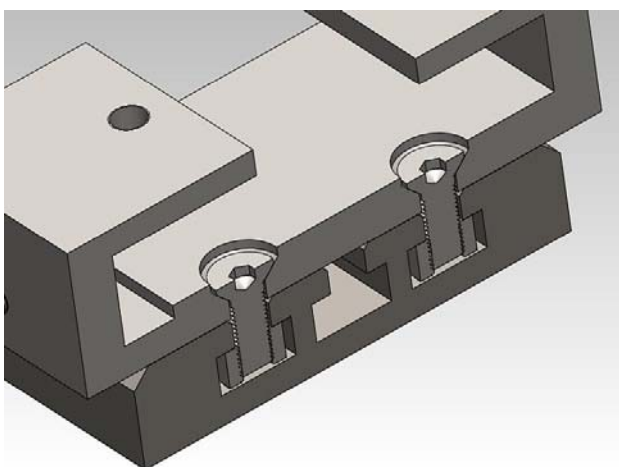


Fig. 11: Section through fastened mechanism of a backing plate on the X-Y table

For this design, six equi-spaced countersunk holes are used, three for each of the two outer grooves of the X-Y table. The fastening mechanism consists of socket screws and hexagonal nuts. The nuts are correctly sized for them to be able to sit into the grooves of the X-Y table but sufficiently big enough to avoid rotating within the groove. This is essential as assess to support the nuts with a wrench during fastening is not possible. In this way, the X-Y table itself becomes the wrench to hold the nut and allow for fastening of the screw and nut together. The screws used allow for easy access to fasten and unfasten the assembly using an Allen key tool. The screws have the correct length to ensure that they do not protrude out of the surface of the backing plate and become obtrusive to the workpiece. Conical countersunk screws were preferred as these create an in-plane (x- and y-axis) supporting force as well as a downward (y-axis) fastening force. This will help optimize the clamping and the support forces of the backing plate when fastened to the X-Y table and minimize vibration.

Furthermore, also presented are the hidden detailed view of the complete assembled support system and this is shown in Fig. 12. The clamping support of the workpieces on the backing plate consists of two long rectangular bars, one for each work piece. The undersides of these bars are lined with a thin layer of Ethylene Propylene Diene Monomer (EPDM) rubber. This is a high temperature resistant rubber layer which gives additional support and effectively reduces vibrations of the workpieces [6-7].

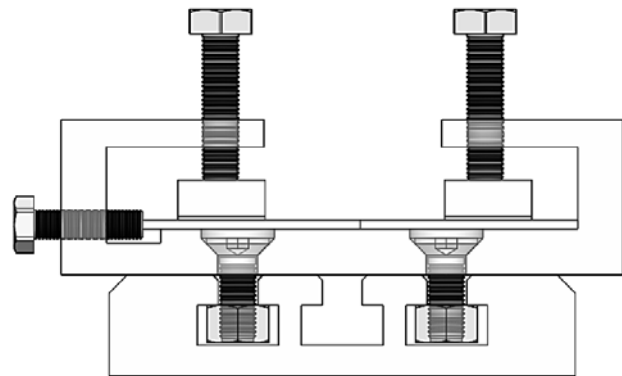


Fig. 12: Detailed view of the assembled support system

The rubber is fused to the metal rectangular bars by means of a special rubber bonding adhesive agent. The clamps were positioned in place by means of vertical hexagonal bolts. These bolts are screwed into tapped holes at the top of the backing plate. The clamps are then wedged between the workpieces and the bolts are tightened. These clamps, together with the bolts, provide the mechanism for exerting a downward clamping force of the workpieces against the backing plate.

The second workpiece clamping system allows the butting faces of the work pieces to be firmly and securely held against each other. This reduces to the minimum size of air gaps that exist between the butting faces of the workpiece. This becomes very critical to ensure a quality weld. This clamping

mechanism is achieved by tapping holes through the front of the backing plate at the same elevation of the workpiece surface and screw in the horizontal hexagonal bolts through these holes until it pushes against the side of the workpiece firmly, making the workpiece also to be closely flushed against each other. A groove is milled in the backing plate to allow better contact between the bolts and the side of the work piece.

A typical free body force diagram of the system is illustrated with Fig. 13. By applying a torque to the bolts (shown in blue) a linear force (shown in red) is exerted to the work piece which is capable of holding the workpieces in a fixed position. The required torque to be applied is related to the optimum force for clamping. The optimum force for clamping is also dependent of the workpiece material.

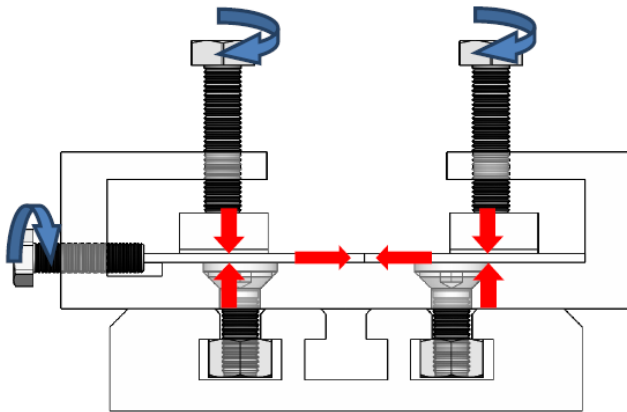


Fig. 13: Major forces involved in a supporting system

Finally, the translucent isometric view of the complete support system fastened to the X-Y table complete with the clamped workpieces is shown in Fig. 14.

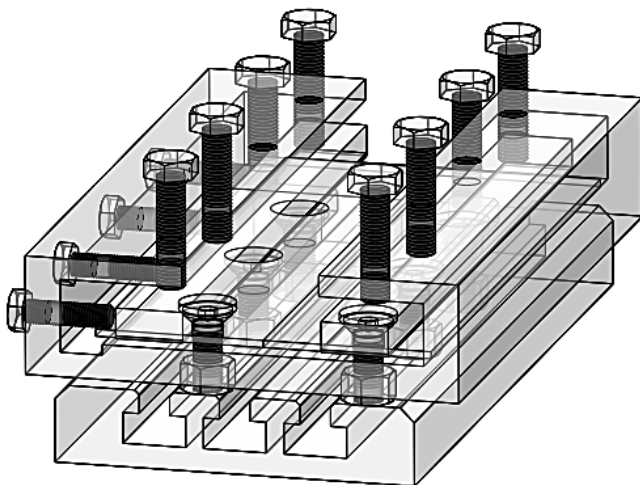


Fig. 14: Translucent isometric View of the Assembled support system

The system assembly of the workpiece, backing plate, clamping and supporting systems were successfully fastened on the X-Y table of the reconfigured milling machine.

## VII. CONCLUSION

Based on the criteria rating between the two design concepts, concept two which has the highest total rating was selected based on the ranking criteria. The selected concept was further subjected to performance analysis. The detailed performance analysis and simulation showed that the concept allow for Friction Stir Welding to be conducted using a typical milling machine. These relatively inexpensive milling machine adaptations allow for the conversion of any milling machine into a specialized Friction Stir Welding machine which is ideal for research purposes. The support system allows for very firm clamping of the workpieces with added vibration resistance features. Various workpiece thicknesses can also be welded using this support system.

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