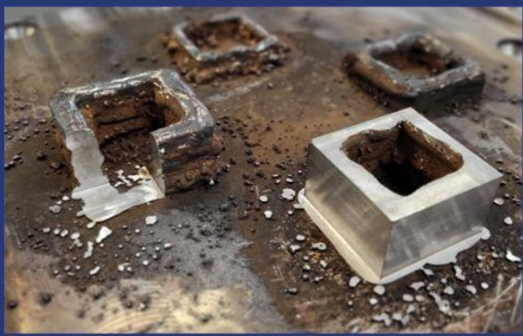
DAMRC

Danish Advanced Manufacturing Research Center

RETROFIT AM FOR CNC-MACHINE.

Retrofitting a CNC machine with welding equipment to allow it to manufacture additive processes while containing its old functions of milling thereby producing a low-cost hybrid CNC-machine.

Target Group:
The results of this report is aiming at helping the Danish machining industry to gain knowledge of the possibilities of retrofitting old machines with welding equipment in a cost-friendly way that will make hybrid machining relevant for a larger part of the industry.



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INDUSTRIENS FOND

Herning Kommune

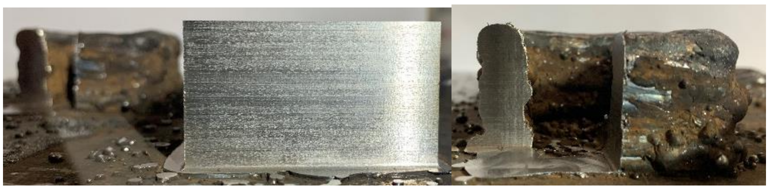
TABLE OF CONTESTS

[This technical report contains information about the P1001-4-3 project Retrofit AM for CNC machine. This project has been driven and performed by DAMRC with funding from Industriens Fond and Herning municipality. DAMRC has within this project partnered with Esprit Nordic and Edeco for software solutions.]

1. EXECUTIVE SUMMARY

Sustainability is one of the major concerns in society. Retrofitting, remanufacturing or repairing old machines helps to grow a circular, more sustainable economy. This project consists of adding welding equipment to an existing CNC machine enabling it to do additive processes while retaining its milling functions. This will lead to a low-cost Hybrid-CNC machine. Therefore, many tests have been done where different wire feed speed or gas flow have been used. In this way it is wanted to find the optimal parameters for the machine to work.

Regarding the results it has been seen that too high wire feed speed leads to bad welding and that it is also very important to maintain the work surface and the wire clean. Although the optimal welding parameters of the machine have not been found, the integration of both machines has been successful, and a couple of workpieces are welded with full burn-through, and subsequently machined with great success.



2. INTRODUCTION

The injection of additive processes in the Danish manufacturing industry is on the rise. More and more companies are taking the plunge and introducing metal 3D printers as a separate manufacturing process. The most innovative machine manufacturers have gone a step further and introduced SLM printing in the machining centers. Common to both solutions are that the technology is advanced and the price for both machines and items is high.

Current benefits

- Minimizing material consumption – Rather than removing a large volume, you can add the small and necessary parts.
- Possibility of combining materials – A subject’s core can be produced with cheap and machining-friendly material such as S235/S355 and surfaces exposed to wear, with a more expensive and stronger material such as Hardox.
- Heat treatment can be minimized as surfaces do not need heat hardening, but instead they can be covered with durable material.
- Possibility of producing geometries that cannot be machined forward.
- Possibility to save material by designing the item based on other parameters and possibilities with its new technology.

Current challenges

- Typically, the investments in new equipment are large and construction and processing takes place separately, which again costs the handling time.
- Workpiece sizes are limited by the geometry of the existing decentralized machines.
- The strength of printed powder metal is often less than of classically machined items.

- The powder used in metal print is harmful to health and therefore requires special attention from employees and company.

The idea to meet the challenge.

The project is based on the existing CNC machines that already are in the industry and aims to develop the basis for an uncomplicated and cost-effective solution, so that companies will be able to work on the existing machines and with the products they already work with today. For the project, we are starting from DAMRC's own 5-axes Mazak V630-5X machining center. For this project, a MIG-welding machine is purchased which is adapted so it can be controlled mechanically and electronically by the machining center. By using this method, we get the following options:

- The industry can use already purchased and written-off equipment and can use the machines' functions and possibilities during the additive processes.
- The companies get additional opportunities to manufacture existing products without costly work processes are introduced.
- The environment does not suffer from the production of new machines when old ones can be given new value.
- The workpieces maintain the strength, as the manufacturing process with the MIG welder is expected to have the same or greater strength than products made with existing manufacturing processes.
- The working environment is already known, as the technology is known from classic MIG welding and the existing extraction in the machines is sufficient.
- No adjustments are required to the machining center that minimize the existing function of the machine. Thus, the machine can continue to be used for the existing tasks it solved before the additive module was added.

3. PRE-ANALYSIS AND LITERATURE RESEARCH

3.1 LITERATURE SEARCH

The idea for the project came from a scientific article about a retrofit kit for a CNC center. The goal of that work was making a process for repairing tools with the machine. Tools for repair can be finished tools such as turbine blades, or mold forms that have been damaged (Campatelli, 2021).

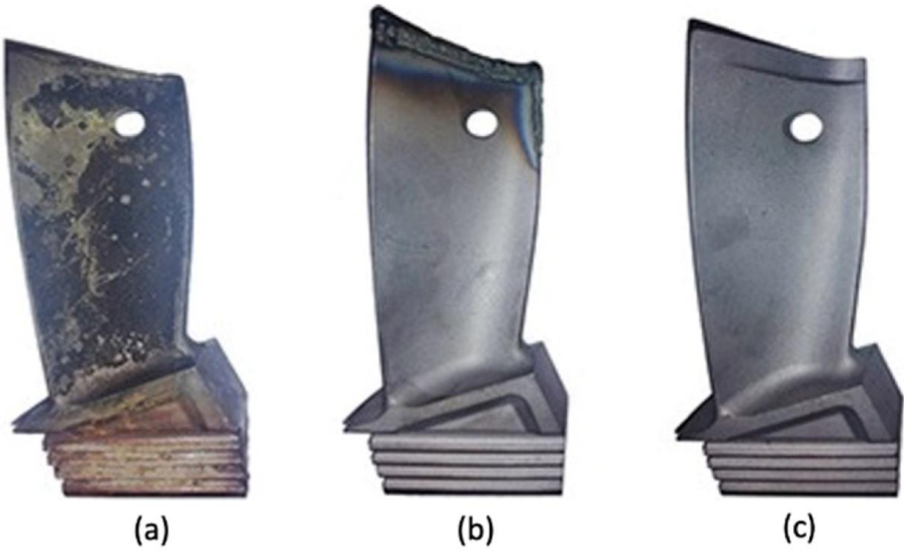


Figure 1. Pictures of turbine blade being repaired. taken from (Campatelli, 2021).

In this article they show how turbine blades can be repaired for a greener circular use of materials. As the figure above shows, figure A is a used and damaged turbine blade, figure B is the repaired blade after welding and before CNC process and figure C is the finished repaired blade. This article has shown that it is needed to design a special tool holder for holding the welding handle. Furthermore, it needs to have a worktable which is electrically isolated from the rest of the machine.

3.2 INVESTIGATION OF MACHINE

In this phase, Mazak CNC center is investigated for integration possibilities. Relay card AP2 has previously been fitted with a Kuka robot which has been switched on and off with the M-codes 113-114-115. The connection is called X301 and is for 250V or X306 for 24V.

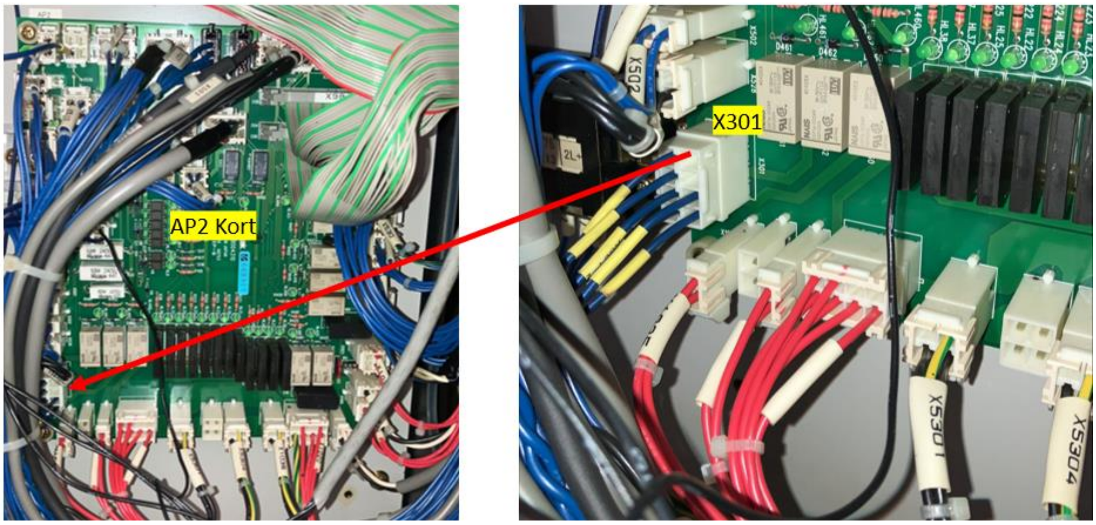


Figure 2. Wiring in Mazak CNC-Center where the Welding machine will be integrated.

Therefore, it has been concluded that there is an existing relay that is not in use which can be used to connect MIG welding systems to a 24V connection which will work with CNC control under the code M115.

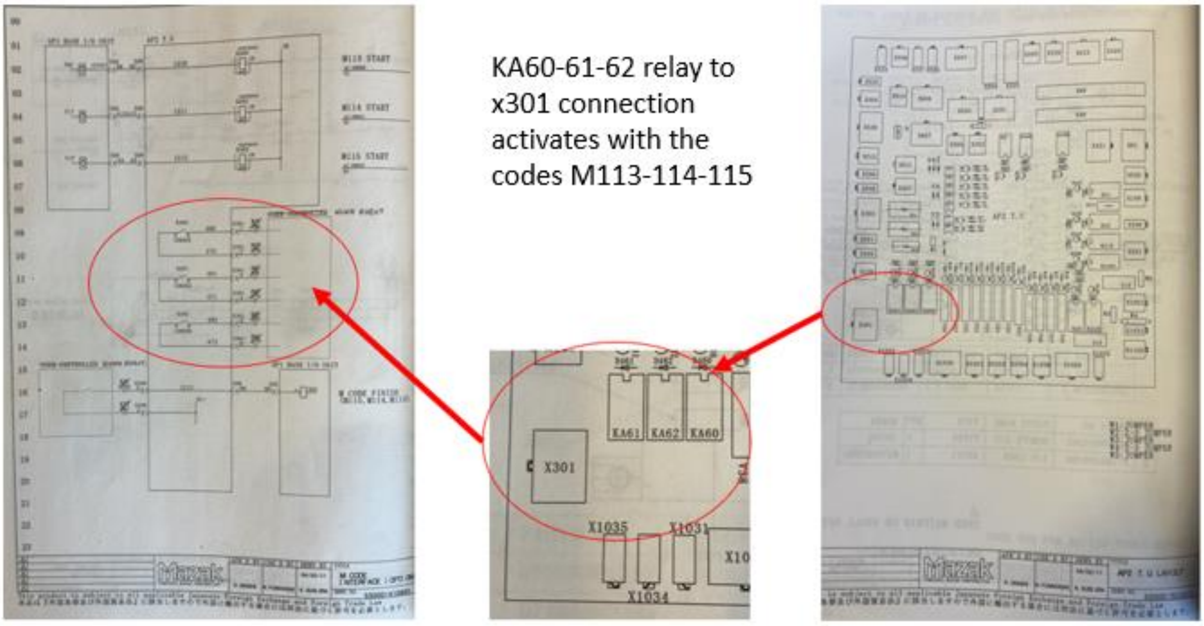


Figure 3. Picture from user's manual for Mazak CNC-center with the M-codes used to activate the Welding machine.

4. HYPOTHESIS

- It is possible to install a MIG welding machine within an old CNC-center and achieve additive manufacturing with the CNC-centers functions.
- The CNC-center will still be able to do a standard milling process after the installation of the MIG welding machine.

5. SUCCESS CRITERIA OF THE PROJECT

5.1 ACHIEVING ADDITIVE PROCESSING WITH SUBSEQUENT SUBTRACTIVE PROCESSING IN ONE AND THE SAME MACHINE.

This project desires a mechanical and electrical integration of a MIG welding machine into a Mazak Variaxis 640 CNC machine. The electrical integration will be a success when the CNC machine can turn the welding machine on and off. The mechanical integration of the welding machine will be complete when the welding handle is integrated on the spindle of the CNC machine.

Furthermore, for additive and subtractive processes to be a reality, a program that can run the toolpath for the processes will need to be made.

6. PROJECT BOUNDARIES

To achieve the goal of successfully integrating a MIG welding machine into at CNC machine it will be necessary to look at the following tasks:

- Isolation of the building plate, so the electrical current will not destroy the machines electrical circuits.
- Development of software for cad/cam that can create machining processes for additive codes like a 3D-printer and afterwards do subtractive processes like a regular CNC machine. Or find partners with competences to do this externally.
- Program toolpath.
- Make the first tests and find the right settings for the welding machine.
- Produce the first part though an additive process and do a subtractive process afterwards.

Through completion of these tasks DAMRC will discover a process that makes simple additive manufacturing possible within a CNC machine and thereafter process it through subtractive machining.

This project will not investigate the more advanced possibilities that come with installing a welding machine in a CNC machine. It will use the 3 axes XYZ on the spindle to perform its additive and subtractive process. It will not investigate more advanced options as using the C and A axes which are available on this machine. Furthermore, when not looking into using the rest of the axial opportunities there will not be investigated how welding at different angles will influence the quality of it. On success of this project a larger R&D project may be initiated to look into these aspects.

Another important aspect for the market success of this product will be an available software solution that can easily handle the new merge of the subtractive and additive processes. As this is something that can easily be commercialized, and it is outside the machining capabilities DAMRC possesses there will not be developed a finished post possessor that can handle both additive processes and subtractive processes.

7. RISK ANALYSES

This part of the report explains the obstacles to not achive the success criteria. Firstly, for the mechanical integration of the MIG welding machine there is a possibility of destroying the electrical boards in the machine with the ampere used for welding. Therefore, the building plate needs to be electrically isolated from the rest of the machine. Even if the building plate is isolated from the machine there is still a chance for loose currents or the welding wire touching the rest of the machine. Therefore, the processes must be handled with care.

Since there is not a scope for developing a new post processor for programming tool path for both additive and subtractive processes DAMRC will need to find a partner in the project that has experience with these types of processes.

8. DESIGN OF EXPERIMENTS AND TEST PARTS

As stated in the literature search it is needed to electrically isolate the plate where the welding will be performed from the rest of the machine. This has been done by integrating a ph500 plate on top of the original worktable (kindly manufactured and delivered by PL Valves) . On top of that a new worktable has been installed - secured by screws. These new screws are isolated with a plastic case. Then on top of the new worktable a series of plates have been manufactured from a 30 mm steel plate to do the welding on. On this plate there is a ground connection secured with a screw, so it will not fall off easily during the additive process.

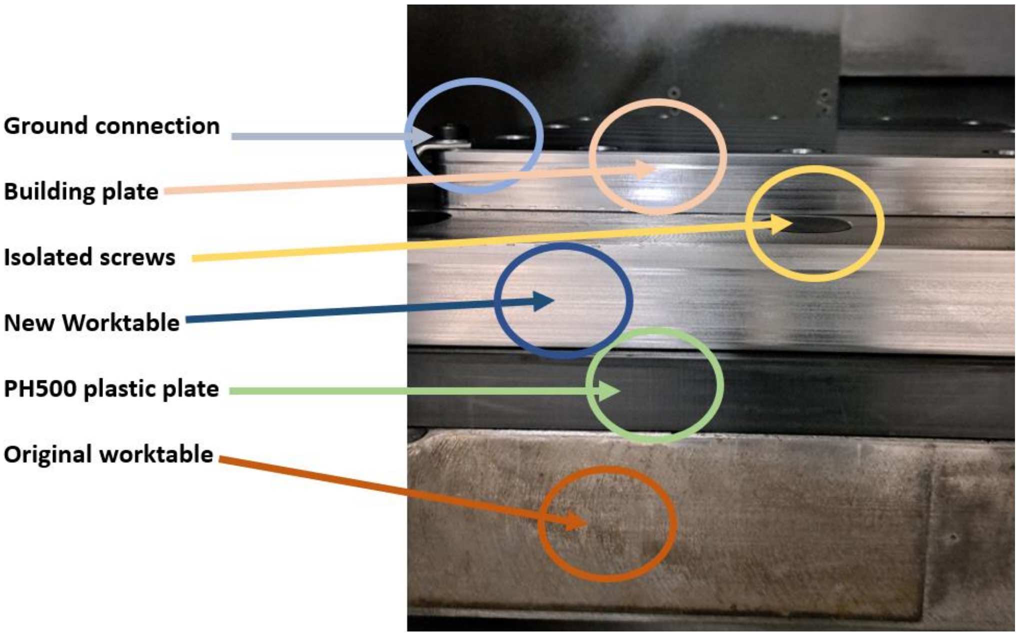


Figure 4. Isolating the CNC center from the welding though a new build with plastic in between.

Esprit Nordic has been chosen to be a partner within this project to handle post processor and CAM programming. Furthermore, they have brought in Edeco who have experience with controlling this particular Mazak CNC center. Therefore, they design the parts and processes attempted with the new setup in the machine, where the build plate is electrically isolated from the rest of the center.

Experiments have been split into two processes. The first part is starting test, where there will be tests attempted as simply as possible to draw straight lines which will be measured and evaluated. With each line the parameters on the Stamos Welding machine will be adjusted to get a better welding. The Stamos Welder has the following parameters which can be controlled.

- Voltage
- Wire Speed
- Arc Current
- Gas Voltage
- Inductance

The second phase of tests will be the actual machining with additive manufacturing. A part will be designed by Esprit Nordic and with the parameters found in phase one. It will be used to machine additives within the Mazak and afterwards do a milling process to refine the workpiece.

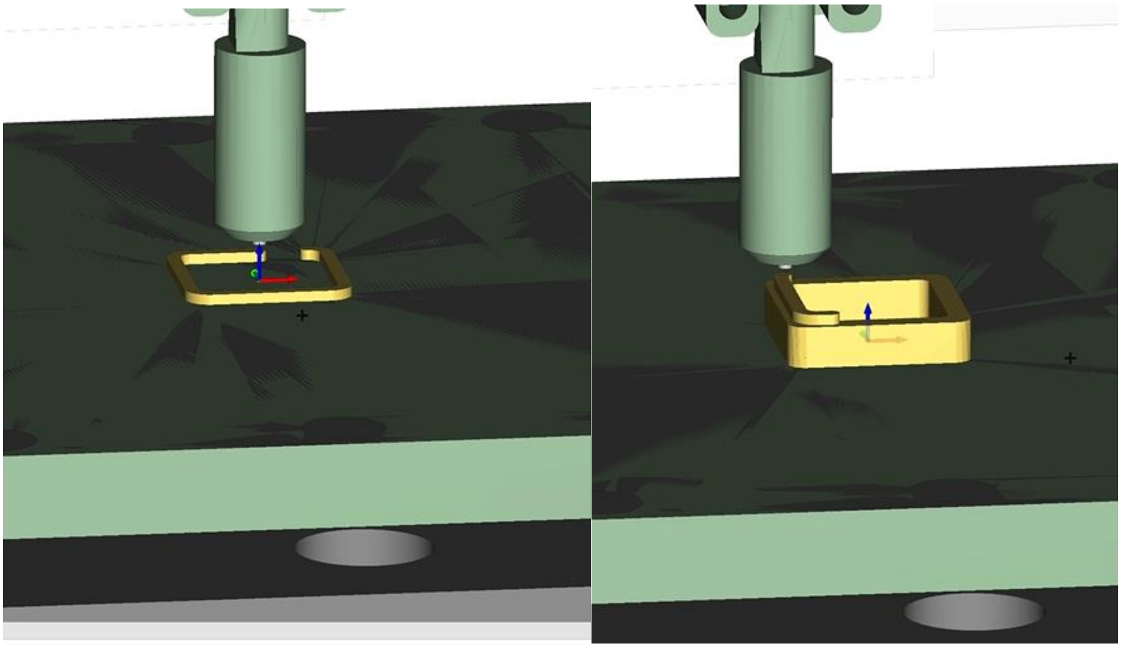


Figure 5. Picture from simulation of the additive manufacturing.

The program developed by Esprit is set to produce simple lines to be measured. Afterwards parameters will be readjusted for a more welding seem suitable for the project. Then the program is set up to build up an object with four walls that will be made through the additive manufacturing. After that the program is set to do a milling process with an end ball mill to even out rough edges and produce a nice finish to the part. To finish, the part will be cut from the plate with a CNC-Saw which is available at DAMRCs technology center.

8.1 DEFINITION OF A GOOD WELDING

A good welding must be uniform, straight and with no slag, cracking or holes. There should not be any dips or craters in the bead. MIG weld needs to be as smooth as possible, with no patterns. A bad MIG weld is indicated by cracking along the weld. Bad symptoms also include any lack of uniformity or dips that prevent the bead from being straight. Additionally, a too-thin bead will not have the necessary strength.

Not all the welds are created equally, so to know if the weld is good or bad it is necessary to look at it: Has it any cracks? Are there splatters around the joinery? Does the seam appear messy? Is the welding line thin? These questions need to be answered to know if the weld is good or not.

Each type of welding technique yields different results. However, if there is a seamless fit in the joint or the evidence of a weld cannot be seen, it would mean that the weld is good.

Characteristics of a bad weld

- Messy appearance, it may look and feel unstable.
- Not a strong and secure joint.
- Too thin.
- Lack of discoloration of the patent metal (it should be about 3,175 mm)

Characteristics of a good weld

- Not seeing the weld at all.
- If there is any visible evidence of a weld it will be uniform and in the form of a bead that has no holes or cracks.
- The weld at the joint has the same strength as the material that is joined.
- Nice appearance.
- A high-quality weld has the required strength to keep multiple pieces of material fused together and perform as an entire structure.

Figure 6. An example of a good weld where the joints do not show any sign of welding (left). An example of a bad weld where it has been partially dressed and the spatter removed (right).

The stability of MIG welding process depends on the current, voltage, welding speed, stick-out, shielding gas and arc length. A fluctuation in the distance between the welding torch and the workpiece may result in a significant change in the current and voltage. The transfer mode, which affects the weld quality, is influenced by current, voltage, and shielding gas. Defects like a poor penetration profile, an undercut, or excessive spatter may appear in an unstable electric arc. Lack of shielding gas, greasy components, an improperly positioned torch, melt-through and wide root holes can all cause welding errors.

As mentioned before excessive spatter is a symptom of bad welding. This can happen due to many reasons, but the main factor is the interruption in the flow of melted weld when the wire is being inserted into the weld. In this situation, the arc is too frigid to maintain the pool and wire at melting temperatures, which causes a stubbing effect on the cable. This may happen at low and high current ranges.

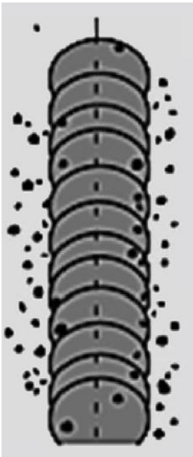
Other problems that can lead to a bad welding are slag and porosity. If these are not controlled, they can lead to less ductile, weaker welds.

Slag, which typically results from aluminum oxide or aluminum nitride particles present in the electrode or base materials, is an issue that is particularly frequent in GMAW welds of aluminum. To remove oxides from the surface of electrodes and workpieces, chemical treatment or a wire brush is required. The slag can also be produced due to the contact of any oxygen with the weld pool, whether it comes from the atmosphere or the shielding gas. As a result, a sufficient flow of shielding gases is required and welding in moving air should be avoided.

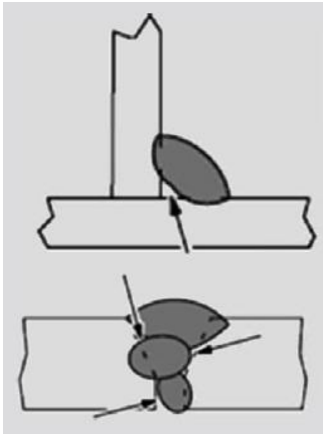
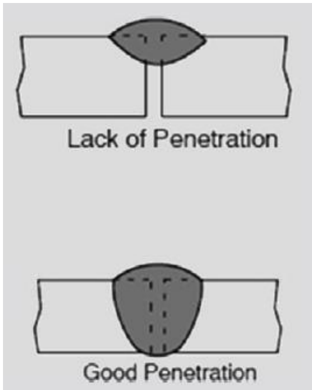
The main factor of porosity is the gas entrapment on the welding pool, which happens when the metal solidifies before the gas escapes. The gas can come from impurities in the shielding gas or on the workpiece, as well as from an excessively long or violent arc. Generally, the amount of gas entrapped is directly related to the cooling rate of the weld pool. Because of its higher thermal conductivity, aluminum welds are especially susceptible to greater cooling rates and thus additional porosity. To reduce it, the workpiece and electrode should be clean, the welding speed diminished and the current set high enough to provide sufficient heat input and stable metal transfer but low enough that the arc remains steady. Preheating can also help reduce the cooling rate in some cases by reducing the temperature gradient between the weld area and the base metal.

The following Table 1 shows some of the most common weld defects and their possible solution and causes.

Table 1. Common MIG defects, possible actions and solutions.

Defects	**Possible causes**	**Solution**	**Picture**
Excessive spatter	Wire feed speed too high	Lower wire feed speed	
	Voltage too high	Lower voltage range	
	Electrode extension too long	Use shorter electrode extension	
	Workpiece dirty	Clean moisture. Grease, rust, dirt, oil and undercoating from work surface	
	Insufficient shield gas at weld arc	Increase shield gas flow and prevent drafts near weld arc	

	Dirty welding wire	Use clean and dry weld wire	
Porosity	Inadequate blanket of shield gas	Ensure proper gas flow	
		Remove spatter from gun nozzle and drafts near weld arc	
		Check for hose leakage	
	Wrong gas	Use welding grade shield gas or change to different gas	
	Dirty welding wire	Use clean and dry weld wire	
	Workpiece dirty	Clean moisture, grease, rust, paint, dirt, oil and undercoating from work surface. Use a more deoxidizing welding wire.	
	Welding wire extends too far out of nozzle	Make sure that weld wire extends no more than 13 mm beyond nozzle	
Incomplete fusion **(Lack of fusion)**	Workpiece dirty	Clean moisture, grease, rust, paint, dirt, oil and undercoating from work surface	
	Insufficient heat input	Select higher voltage range and/or adjust wire feed speed	

	Improper welding technique	Adjust work angle or wide groove to access bottom during welding	
		Keep arc on leading edge of weld puddle	
		Use correct gun angle of 0-15 ^{o}	
		Momentarily hold arc on groove side wall when using weaving technique	
Lack of penetration	Improper joint preparation	Metal too thick. Joint preparation and design should provide access to bottom of groove while maintaining proper wire extension and arc characteristics	
	Improper weld technique	Maintain normal gun angle (0-15 ^{o}) to achieve maximum penetration	
		Keep arc on leading edge of weld puddle	
		Make sure that weld wire extends no more than 13 mm beyond nozzle	
	Insufficient heat input	Select higher voltage range and/or wire feed speed	
		Reduce travel speed	

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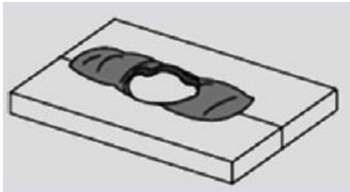
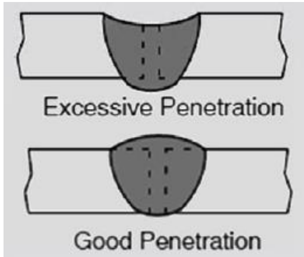
<tr><td rowspan="2">Burn-through</td><td rowspan="2">Excessive heat input</td><td>Lower voltage range and reduce wire feed speed</td><td rowspan="2"></td></tr>
<tr><td>Increase and/or maintain steady travel speed</td></tr>
<tr><td rowspan="2">Excessive penetration</td><td rowspan="2">Excessive heat input</td><td>Lower voltage and reduce wire feed speed</td><td rowspan="2"></td></tr>
<tr><td>Increase travel speed</td></tr>
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9. VALIDATE, ANALYSES AND QUALITY ASSURANCE

Before the tests were conducted there have been produced at test arc for collecting the test data. On Table 2 the test arc is shown with data from the first test.

RETOFIT: welding trails.												
Trial no.	Seam thickness:	Welding voltage step:	Welding amp step:	Wire Speed step:	Welding height: (DMU)	Welding speed: (DMU)	Wire Meterial	Wire thickness:	Gas pressure:		Welding Rating 1-10	Comments
1	-	27,9	7,8	7,7	-	-	C2/S355	1,2mm			2	05-12-2022: SIS Welding startet machine didnt move, so only welding on start point. 05-12-2022: Rmp: welding didn't sound right, probably need adjustment, but we can first adjust the parameters on the welding machine when the system is running, when we can see have fast the Mazak moves, and then ajust on the fly, as there is no connection between the Mazak and the welding mashine on that parameters yet.
2							C2/S355	1,2mm				
3							C2/S355	1,2mm				
4							C2/S355	1,2mm				
5							C2/S355	1,2mm				
6							C2/S355	1,2mm				
7							C2/S356	1,2mm				
8							C2/S357	1,2mm				
9							C2/S358	1,2mm				
10							C2/S359	1,2mm				
11							C2/S360	1,2mm				
12							C2/S361	1,2mm				
13							C2/S362	1,2mm				
14							C2/S363	1,2mm				
15							C2/S364	1,2mm				
16							C2/S365	1,2mm				
17							C2/S366	1,2mm				
18							C2/S367	1,2mm				
19							C2/S368	1,2mm				
20							C2/S369	1,2mm				

Table 2. Documentation, comment section and data from the first test.

Each successful test will be measured and evaluated, and welding parameters will be adjusted.

9.1 TESTS

First test attempt ended up with a welded dot in the middle of the steel plate (Figure 7) since the machine could not run while using the M-code made for the integration. This was unknown to DAMRC when integrating the Stamos Welding machine.

Figure 7. First welding attempt in CNC-center

It was discovered that the machine was unable to move while it had sent a signal to the welding machine to turn on. This probably is because the integration used was for an old Kuka robot and the machine is not supposed to move while a robot is working. A new integration was needed, so it has been attempted to integrate the Stamos Welding equipment with the coolant integration. Therefore, the on/turn off coolant function can be used to start and stop the welding equipment.

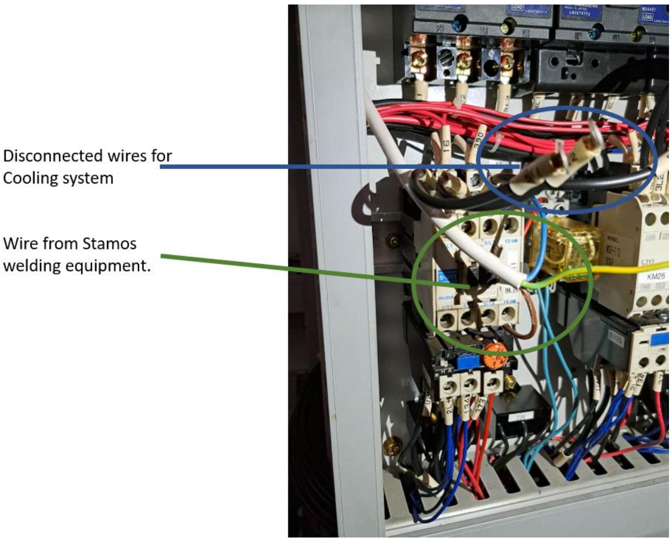

Figure 8. New integration of welding equipment

This integration worked and made it possible to move the spindle while the welding machine was turned on. Thanks to this, the first tests were performed, which will be described in the following section.

9.2 WELD QUALITY

The first and second trials results are not good welds. The second trial has a lot of holes which is a characteristic of a very bad welding. In fact, the first trail is just a dot (Figure 7) and can really be categorized as a weld.

The third test (Figure 9) shows quite good welding. Although it is not uniform at all its close to uniformity. However, it is thin so it may not have the necessary strength. In this test there is no evidence of spatter, which can mean that the gas flow and the voltage used were correct. On the other hand, 3.1 and 3.2 tests show a worse welding. 3.1 test shows porosity problems as it has some holes. The reasons for these holes can be many, inadequate blanket of shield gas and/or dirty workpiece or welding wire. 3.2 test does not show any hole, but it is not uniform either. This test shows excessive spatter that may have been caused because of dirty welding wire or workpiece. The spatter usually appears when the wire feed speed or the voltage is too high.

Figure 9. Results of test 3.

For test 4 the gas flow has been higher than for the previous tests. It is not uniform at all, but it has no holes. However, it has some spatter, so the voltage or the wire feed speed have been too high. Another reason for spatter to take place is the electrode extension. If this is too long, it will produce spatter. In a few words we cannot say that it is a very bad weld, but it is not a good one at all.

The gas flow used in test 5 was the same as in test 4. This test shows more excessive spatter than the previous one. However, there is no evidence of why this happened, as both tests have similar data used. But it may be because of the same reasons that were mentioned before. Also, it is not uniform at all.

In tests 6, 6.1 and 6.2 the wire speed has been increased which has led to excessive spatter in all the tests. Test 6 is the one with the most spatter and it is not uniform. Tests 6.1 and 6.2 are very similar, both have spatter and are not uniform. They have some holes which indicate that there is porosity. Therefore, this means that the gas flow may not be the correct one or that something can be dirty (workpiece of welding wire). The only difference between 6.1 and 6.2 tests is the gas flow, as in 6.2 test, it is higher. However, this has not led to any notorious difference between them.

Figure 10. Results of test 6.

To sum up we can say that the only trials that were near of being good welding are 3 and 3.1. Also 3.2, 4 and 5 tests were not bad welding.

Test number 9 was cut in a milling process to achieve hybrid machining (Figure 11). It was cut so the outside walls and top of the piece got a finish. There are not any visible signs of layers within the wall, and it seems just as if the part had been made from a normal piece of S365.

Figure 11. Test 9 after milling it seen from above.

As can be seen in the figure above, the walls from the outside part are perfectly milled and it can be seen uniformity in it.

After the welding was done the tests were removed from the plate. This way it can be seen how good the welding was, if it was well penetrated in the plate or not. The following Figure 12 shows how the plate was after the welding was removed.

Figure 12. Close up of test X after removal.

Overall, it seems that the whole piece has been well welded to the plate. The outside part was better welded than the inside one as there is a sign that something was welded there around all the outside part. While on the inside part there are some parts where this sign of welding does not appear.

10. DISCUSSION

This section is about questions raised during the project that have not been answered by the results.

In this project we have successfully accomplished making parts with additive manufacturing using the features of a CNC machine and a standard welding machine. There have been tests showing some bad weldments where cooling time between layers have been added but not enough time to test for optimal parameters. Since the project at focus on making the process possible there haven't been a focus to make the test necessary for finding optimal parameters for the feed rate on the wire, and feed rate on the spindle, but parameters that make the process possible have been found. There have not been found optimal parameters for cooling time between the layers or layer height. Furthermore, the impact of different thread thicknesses would have in the results due to the heat needed to melt a thicker wire has not been investigated.

To print the parts only 3 axes of the machine have been used. Therefore, it has not investigated methods for using the features of 5 axes additive manufacturing. This would require new software and programming of G codes but should not be impossible. Using more axes for additive manufacturing will open possibilities for making more geometrically advanced parts.

The parts produced have been manufactured using S355. There is a possibility in changing the thread and thereby making parts composed of multiple materials. This has been described as a possibility in the benefits of this technology but has not been tested yet.

CO_2 emissions have not been measured by this additive method of production. In a world and industry where the topic of emissions is a highly discussed topic it will be more than relevant to investigate power usage of this new additive manufacturing process compared to a conventional milling process. This study can be done by measuring the power usage and comparing material usage and waste.

11. CONCLUSION

The start of this project has been focused on making an integration of a Stamos Welding machine to a Mazak Variaxis 630. This has been done by integrating the start stop signal of the welding machine to the coolant signals of the machine. Thereby the coolant cannot be turned on accidentally and burn the electrical circuit in the machine as it now turns on/off the welding machine. That is why this integration method is safe and doable for this type of CNC machine. Esprit has been a reliable partner within the project to assist with programming of the machine to do the additive manufactured parts.

Spatter

Considering all the tests done, many conclusions have been reached. Firstly, wire feed speed impacts excessive spatter directly. The higher the wire feed speed is, the higher the excessive spatter is. This can be seen in the trials; when the wire feed speed was 7,7 most of the welding did not show spatter. However, when the wire feed speed was increased to 15, all the tests showed it. Amperage is determined by wire feed speed, so if this is too high spatter will appear. To correct it, the amperage should be lowered by decreasing the wire feed speed or increasing the voltage. In this way the uniformity of the weld will also improve. Nevertheless, it is not possible to draw any conclusion about the amperage from our tests as in all of them the amperage used has been the same. Also, voltage has been the same for all the trials so we cannot draw any conclusion that this is related to the spatter. Nevertheless, many studies show that spatter levels increase when the voltage is too low. So, to avoid that the voltage needs to be increased until spatter decreases.

Porosity

Porosity has been one of the major problems that welds have shown. Many tests have shown holes which are a sign of a bad weld. This can be related to the shield gas, the welding wire, or the workpiece itself. When these last are not clean, porosity may appear. To not have porosity in the welds it is very important to maintain not only the work surface clean but also the welding wire. Indeed, a dirty workpiece or welding wire will lead to bad welding.

Gas flow

The shield gas also impacts porosity and excessive spatter. Using the wrong gas may affect weld quality. However, it has not been possible to make any relation between the weld quality obtained on the tests and the shield gas flow. But it is important to prevent drafts near the welding arc, if not porosity and other defects may appear on the weld.

To finish, the CNC speed also affects weld quality, a high CNC speed results in poorer quality welds as the first tests have shown.

12. Bibliografi

Campatelli, G. (2021). *Design and Testing of a WAAM retrofit kit for repairing operations on a milling machine.* Firenze: MDPI.

13. APPENDIX

13.1 APPENDIX A - PHOTO OF THE TESTS

Figure A1. Results of test 2.

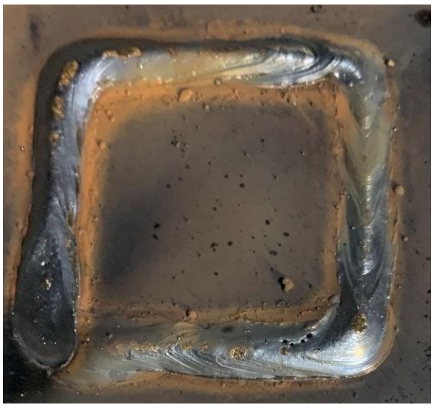

Figure A2. Results of test 3.1.

Figure A3. Results of test 3.2.

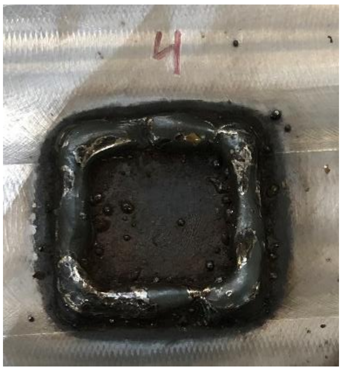

Figure A4. Results of test 4.

Figure A5. Results of test 5.

Figure A6. Results of test 6.1.

Figure A7. Results of test 6.2.