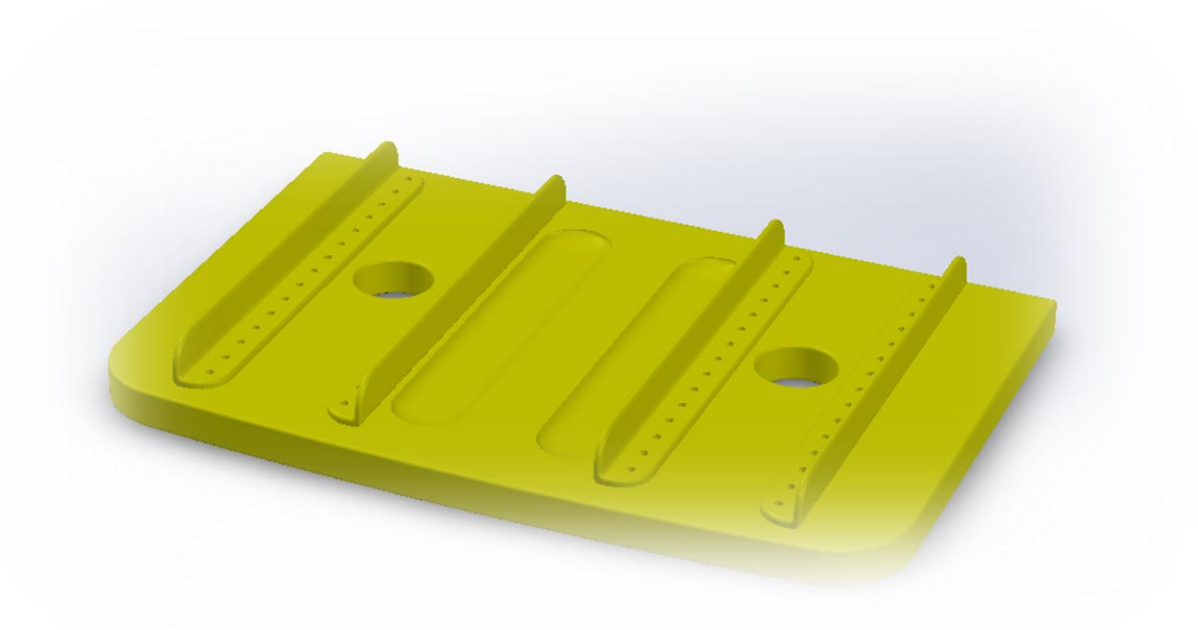


MARCH 15, 2019

ADVANCED PROCESSES AND MATERIALS (M6X00414)

HELICOPTER COCKPIT FLOOR MANUFACTURING EVALUATION



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1.0 Executive Summary

The intention of this report was to determine and review two alternative manufacturing solutions for an organisation working within the aerospace sector. The Organisation would like to modernise, expand and invest in new technology to help strengthen and better compete within their industry sector. The management team had provided details of one of their products and requested that alternative technologies were compared, with regard to their advantages and disadvantages, in comparison with CNC milling.

To provide a detailed technology review and to limit the multitude of manufacturing technologies available in today's industry, part assumptions were added to the product. Based on these assumptions two non-traditional technologies were selected which had the required capability of manufacturing the part. The three technology work flows were charted through process mapping to record the essential features of each technology for analysis. A criterion was created of essential requirements against which, each Manufacturing System could be measured against. This criterion was weighted in order of importance, and entered into a Selection matrix to obtain a quantitative measure for each of the three manufacturing systems.

The process evaluation, literature review and quantitative analysis all would suggest that the organisation's current traditional method of manufacturing this part through CNC Milling is the most efficient and cost effective. However, this should not however suggest that CNC Milling is a better process for all applications. What has become evident throughout this project is the strengths and weaknesses of each technology, and how each process can be complimented by one another. Abrasive waterjet cutting is often used for bulk material removal before CNC Milling, or CNC Milling can be used to provide added precision to complex DMLS parts. If the technology review had been considering a different part, with different requirements, then either of the other two technologies could have been rated differently.

The conclusion of this review was to advice the Organisation that DMLS technology is not quite ready to manufacture this part economically. However, I believe there is value in further analysis into the feasibility of introducing a three-axis abrasive waterjet cutting machine, as a pre-process bulk material removal operation prior to CNC Machining.

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2.0 Introduction

2.1 Problem Statement

Organisation X manufactures a variety of aerospace components and would like to modernise, expand and invest in new technology to better compete within their industry sector. Organisation X has supplied details of one of their current products, which is a helicopter cockpit floor (Appendix A). The company requires two alternative manufacturing solutions to the CNC milling process currently in place. These alternative solutions must be non-traditional, improve surface finish quality and will require post process heat treatment. The management team of the company have requested that the two alternatives are compared and contrasted, with regard to the advantages and disadvantages of both processes in comparison with CNC milling.

2.2 Part Specification Assumptions

To provide a detailed technology review and to limit the multitude of manufacturing technologies available in today's industry, part assumptions were added to the product detail:

- The part material must remain aluminium.
- Process capability must meet assumed dimensional specification within drawing number M6X414-01 (Appendix B).
- Current process is subtractive and starts with a solid block of material (blank). However, there is no constraint in manufacturing the final component in parts.
- Underside is flat and has no other detail.
- Assumed surface finish roughness is currently 6.3 Ra (μm). Please refer to Appendix*** for description. Therefore, surface finish must be $< 6.3 \text{ Ra } (\mu\text{m})$.

2.3 Technology Selection

Evaluation of the process requirements and research into current non-traditional manufacturing technologies from literature and journal articles provided two potential solutions to the manufacturing process:

- Abrasive Water Jet Cutting
- Direct Metal Laser Sintering

However, to fully understand the current state and to elaborate on the advantages and disadvantages of both processes in comparison with CNC milling; analysis of the CNC Milling process was also necessary.

3.0 Manufacturing System Research

3.1 Introduction to CNC Milling

The CNC Milling process is a subtractive traditional technique which removes material through a plastic shearing or controlled fracture action, which is facilitated by a rotary cutting tool. This process is dependent on the tool material being harder than the work material, which introduces a constraint into material selection suitable for this technology. CES Edupack (2018) states that ‘metals with a hardness below Rockwell 45, some plastics and ceramics can be profiled through CNC Milling’. CNC Milling is generally a secondary process, materials are first forged, cast, rolled or built (additive manufacturing). These bulk deformations or build processes are followed by material removing operations to reach final dimensions and surface quality tolerances (Liang and Shih, 2016; Groover, 2011).

Milling machines can shape, or add details such as slots, threaded holes and pockets to parts. The computer numerical control (CNC) allows for extremely close tolerances, repeatability and increased throughput with less labour hours. The system can read design information directly from CAD drawings or models, preventing any errors between designer and production. The system software codes such as NC code, G-code and ISO code are all converted from a project’s CAM or CAD design. This information is then translated to machine coordinates for tool paths throughout the process. Program files can be stored or transferred for different parts allowing for flexibility of the machinery. The program controls the path of the cutting tool instead of relying on the shape to create the part contour. Therefore, the same machine tool can be used for many different parts. Modern CNC Milling machines can operate within six axes to provide complex parts with high levels of detail, surface finish and accuracy. The process is flexible, agile and extremely economical for prototyping, custom design and small batch manufacturing. However, the process does have limitations, which include the part size is limited to the size of the machine bed. Restricted axis movement and tool path geometry, subtractive processes generate excessive waste. Some hard and brittle materials cannot be machined and internal shapes or features are not possible. (Wright, 2016; Liang and Shih, 2016).

3.2 Introduction to Abrasive Water Jet Cutting (AWJC)

Abrasive Waterjet machining is a non-traditional, Subtractive Manufacturing technology which uses an abrasive garnet suspended in a high-pressure jet stream to provide a powerful and versatile cutting machine through erosion. The last three decades has advanced AWJC from a relatively basic cutting tool in the 1980s to a refined system working within sectors ranging from aerospace to the food industry (Alsoufi, 2017). Abrasive waterjet machines do not generate or introduce any heat during machining because of the water acting as a coolant. Complex or intricate parts can be cut which are not subjected to any thermal distortion and the process does not create a heat affected zone. Post or secondary machining processes can easily be implemented such as thread-cutting as original material properties are maintained. Part designers are free to create detailed components as waterjet cutting has a very narrow cut which is subject to low cutting forces. Complex contours and shapes can be created which would be impossible with conventional manufacturing processes. The process has very low waste which is advantageous when cutting expensive material such as Titanium. Within sectors which deal with difficult to cut materials such as ceramic or composite laminates, this technology has become very favourable. However, AWJC has its limitations and becomes less economical when processing thick materials because of the necessary slow cutting speeds required to prevent tapered edges on the kerf width. The process generates loud high-frequency noise and is prone to creating messy working environments. (Alsoufi, 2017; Waterjetmachines.org, 2019).

Burnham (as cited in Wright, 2016) reasons, ‘What’s the most common hard material cut? It’s mild steel, which everything can cut—plasma can cut it, laser can cut it, punches, mills, routers, saws; everyone can cut mild steel. Moving up to plate, still a lot of processes can cut mild steel in plate. Basically, as you get away from the super-common materials into the more exotic materials, and you get a thicker, like up to a foot thick, then you’re getting into the realm where waterjet shines’.

AWJC systems are available in one, two and three-dimensional production applications. The more common Two and Three axis machines have been used within industry for some time for 2D applications and profiling shapes. However, recent innovation has developed this technology for motion within five, six and even seven axes. This 3D cutting alternative is similar to other older systems where a cutting head such as oxyfuel or plasma is mounted onto a robotic arm. These systems were predominantly used for cutting around vessels or following a contour of a formed metal sheet to trim an edge. The 3D system is often referred to as a robotic waterjet system and either holds the workpiece for manipulation under a fixed head; or the robot can carry the cutting head. A robot with

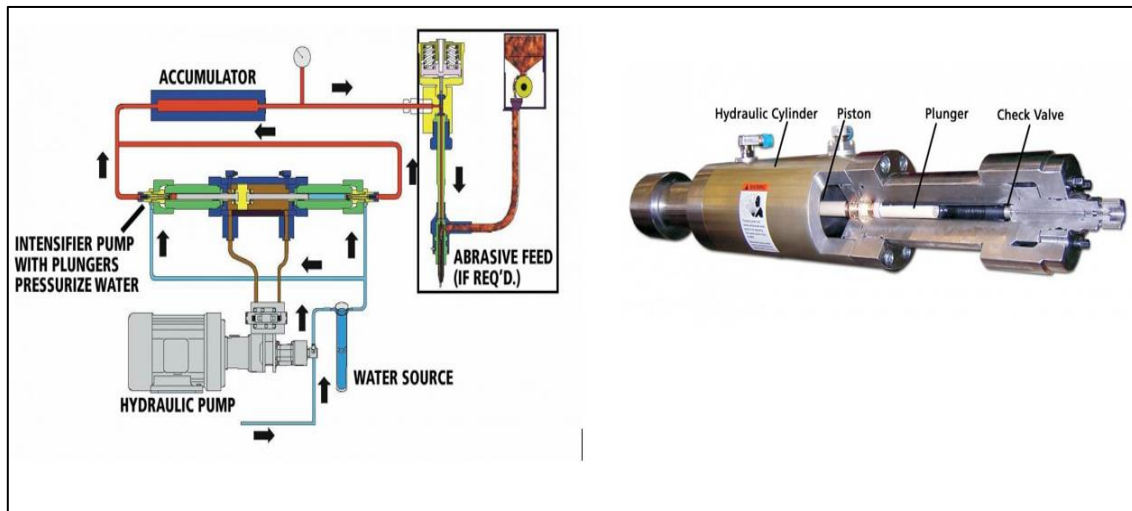
an abrasive waterjet cutting head can be mounted on a seventh axis linear rail to provide a large working envelope. The robot can be inverted or mounted to a wall, to work above or in between different part details (Trushenski and Cranston, 2018).

‘A standard long-reach robot used for waterjet has a horizontal reach of about 122 in. Wall mounted; the robot has a vertical reach of about 200 in. A standard abrasive waterjet robot system has a work envelope of 75 by 88 in., and other robot models with longer reach capabilities are available for larger work envelopes (Trushenski and Cranston, 2018).

Within today’s industry 2D systems are the most popular, where the cutting head is driven in X-Y axis and the Z axis is controllable in order to adapt to non-flat surfaces. The control is typically integrated with current CAD/CAM systems, which optimises the process of cutting curvatures and shapes. Unlike milling machining the jet produces no tangential forces on the part. Therefore, work holding clamps are only required when machining light materials to prevent fly-away caused by water turbulence. This facilitates quick turnaround on material changes during production and optimises machine availability. Three Dimensional machines have a 5 axis cutting head, which can produce conical cuts from flat material, perpendicular holes and cut chamfers. These systems are also capable of cutting out shapes in components not usually accessible. Table sizes typically range from 1x2m to 3x4m; however, larger machines are manufactured. (Kmt-waterjet.com, 2019).

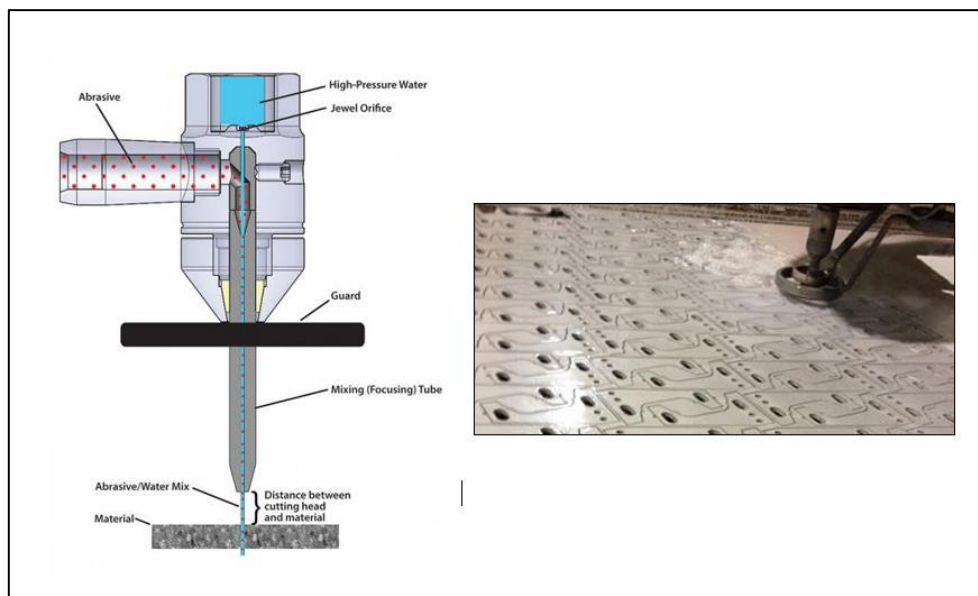
Unlike many other manufacturing systems AWJC does not generate harmful fume or smoke and a typical machine may be sited anywhere that a conventional machine tool can, dependent on size constraints. Parts do not become contaminated with lubricants or cutting oils and only require a quick hose wash to remove excess garnet post process. The machining process produces excess water containing very small amounts of solid fines, which may require filtering dependant on local regulation before disposal to a waste water drain. Garnet and Kerf material waste is often sent to landfill, however, recycling for reuse is possible. If the material being machined is harmful (lead, beryllium, etc), both waste streams must be further processed to meet environmental legislation. (Omax.com, 2019)

Abrasive waterjet machines generate the high pressures necessary to create the high velocity cutting stream either with an intensifier or direct-drive pump. The diagrams below illustrate the process using an intensifier pump. Where, an electric driven hydraulic oil pump delivers oil at 2750 psi into the intensifier. The intensifier increases domestic water pressure from 50-60 psi up to 55,000 psi. This is achieved by the amplification of the larger surface area of the hydraulic piston, the surface area is 20 times greater which amplifies the water pressure to 20 times that of the oil (Nambiath. 2016).



(Nambiath. 2016; Performancewaterjet.com, 2018).

The high-pressured water is then delivered through stainless-steel high-pressure pipe and into the cutting head. Further precision is introduced by focussing the stream through a ruby, sapphire, or diamond orifice. This precise water stream passes through a mixing chamber where abrasive garnet is drawn in through a venturi action (Nambiath. 2016).



(Nambiath. 2016; Performancewaterjet.com, 2018).

3.3 Introduction to Direct Metal Laser Sintering (DMLS)

Direct metal laser sintering is a non-traditional additive manufacturing (AM) process. AM is frequently referred to as 3D Printing, which includes numerous individual processes that differ in their method of layered manufacturing. These processes vary depending on the technology and type of material used. The processes have been classified and grouped into seven categories:

- VAT Polymerisation
- Metal Jetting
- Binder Jetting
- Material Deposition
- Powder Bed Fusion
- Sheet Lamination
- Direct Energy Deposition

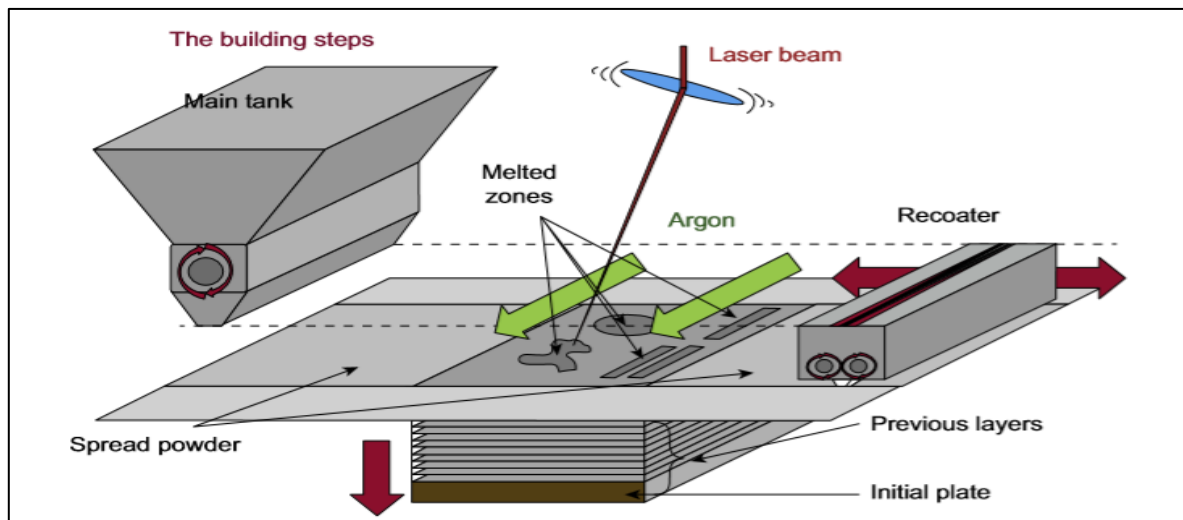
(ISO/ASTM 52900, 2015)

DMLS is contained within the Powder Bed Fusion (PBF) group along with Selective Laser Sintering (SLS), Electron Beam Melting (EBM), Selective Heat Sintering (SHS), and Selective Laser Melting (SLM). The PBF processes either melts or fuses powdered metal such as aluminium, stainless steel, titanium and some niche alloys using a precise high-powered laser. The process builds accurate and complex geometries not possible with other metal manufacturing methods directly from CAD models. DMLS parts are stronger and denser than investment casted parts and have faster turnaround time as no additional tooling is required. The surface finish of DMLS is comparable to fine investment casting and requires post processing for improved finishes. Parts are often machined or ground post process to obtain precision, surface finishing includes media blasting and polishing. The main disadvantage of this process is currently the high associated cost and part size constrictions because of the small build chambers. Which reasons why the primary usage for this technology is generally limited to complex oil and gas components, medical guides, aerospace parts and functional prototypes. Further development, research and demand for this technology should make things more cost effective in the future. Brandt, (2017) predicts that the 'machine building chamber size will increase to 2m³ by 2020'.

The DMLS process involves spreading a thin layer of powdered metal across the surface to be printed within a build chamber. This powder is then sintered using a laser which heats only to the point of fusion at a molecular level and does not fully melt the powder. The atmosphere is controlled within the chamber and filled with an inert gas to protect the metal during fusion and prevent porosity within the build structures. Layers of powder are added and the process is continued, building one cross section at a time. Once a 3D object is formed, it is left to cool and excess powder can be recovered and recycled from the build chamber. The process eliminates any need for jigs, assembly fixture and

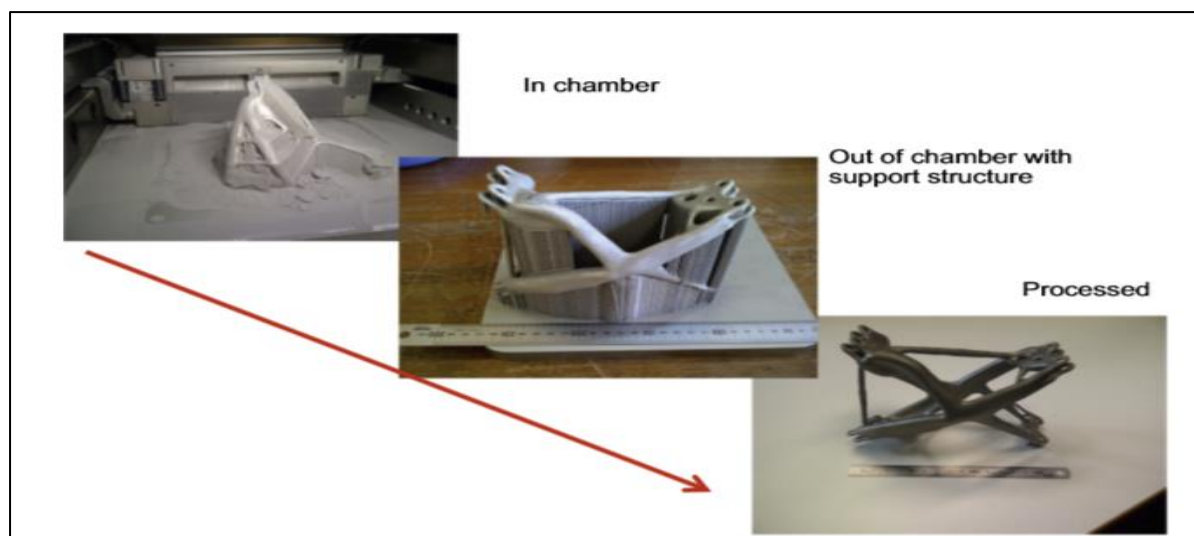
tooling. Another advantage given from Mahmud, et al (2018) is that 'DMLS produces objects free from any residual stresses and internal defects'. Residual stress is common in traditional manufacturing techniques such as casting or welding, it is sometimes necessary to relieve these stresses through post heat treatment operations to prevent premature failures (Brandt, 2017; Claus, 2015).

The below illustration provides all of the main components involved within the process. The excess powdered metal is not recovered until the end of the process, which also helps to support the part during the build.



(Brandt,2017).

Depending on the design and build orientation support structure are often required and will need post processing to remove. The illustration below shows this progression from the build chamber to the finished part.



(Brandt,2017).

4.0 Analysis

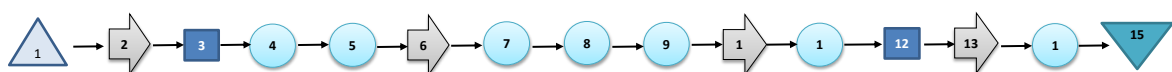
4.1 Work Flow Charting

To gain a detailed understanding and to help facilitate later analysis and conclusions, an American Society of Mechanical Engineers (ASME) process map was modelled for each technology. The process map illustrates the predicted steps required within each system to manufacture the Helicopter Cockpit Floor; the process knowledge was gained from the academic literature and current technology research conducted.

‘The charting of work flows, working processes, systems and procedures is a useful way of recording the essential features of a work situation for subsequent analysis’ (IMS-Productivity.com, 2019).

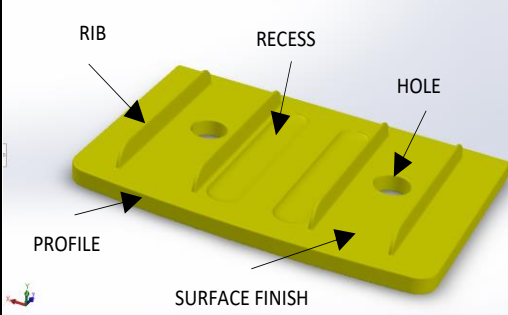
4.1.1 CNC Milling Process

CNC Milling Predicted Process Map (ASME).		Operation	Transport	Delay	Inspection	Store	Receive
No	Process Step						
1	Aluminium must be pre-cut or purchased at a manageable size to fit on CNC Machine bed						✓
2	Transport Batches of blanks to the CNC Milling machine and maintained WIP with Kanban		✓				
3	CAD Drawing inspected for conformity and part ID				✓		
4	Machine setup - Program Selection/File Transfer	✓					
5	Machine setup - Selection of tooling, replace wipers/inserts, etc	✓					
6	Load blank onto machine		✓				
7	Alignment and fix to machine bed	✓					
8	Machining Process	✓					
9	Unclamp from machine bed and remove swarf from part and machine	✓					
10	Unload part		✓				
11	Debur part	✓					
12	Inspection				✓		
13	Transport to Heat Treatment Pcess		✓				
14	Heat Treatment Process	✓					
15	Packaging and storage					✓	



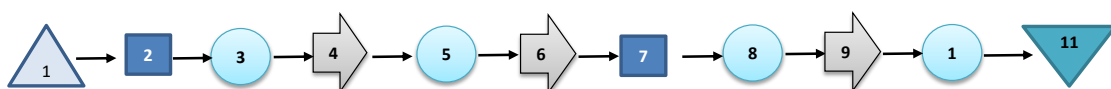
(IMS-Productivity.com, 2018).

An additional table was drafted to illustrate each technology's capability on producing the different part features of the component. As illustrated below; the CNC Milling process is capable of producing all part details without any secondary processes. The only barrier to this process is that some level of pre-process is required to form a blank that is able to fit within the machine. Once the part is loaded onto the machine bed, the process can add all feature to the necessary tolerances and achieve the surface finish in one operation.

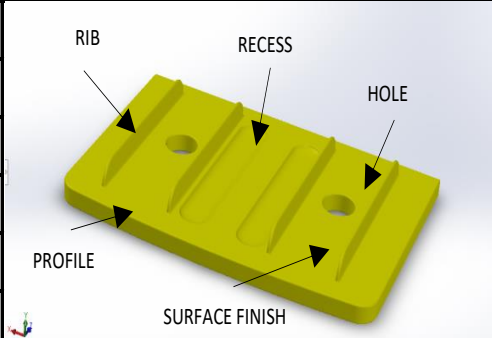
CNC MILLING PROCESS - PART DETAIL CAPABILITY		
PART DETAIL	CAPABILITY	
Profile	✓	
Hole	✓	
Rib	✓	
Surface Finish	✓	
Recess	✓	

4.1.2 AWJC Process

AWJC Predicted Process Map (ASME).		Operation	Transport	Delay	Inspection	Store	Receive
No	Process Step						
1	Aluminium plate delivered to AWJC machine and maintained with Kanban						✓
2	CAD Drawing inspected for conformity and part ID				✓		
3	Machine setup - Program Selection/File Transfer	✓					
4	Load plate onto machine		✓				
5	Machining Process	✓					
6	Unload part		✓				
7	Inspection				✓		
8	Secondary fabrication process (bracing)	✓					
9	Transport to Heat Treatment Process		✓				
10	Heat Treatment Process	✓					
11	Packaging and storage					✓	

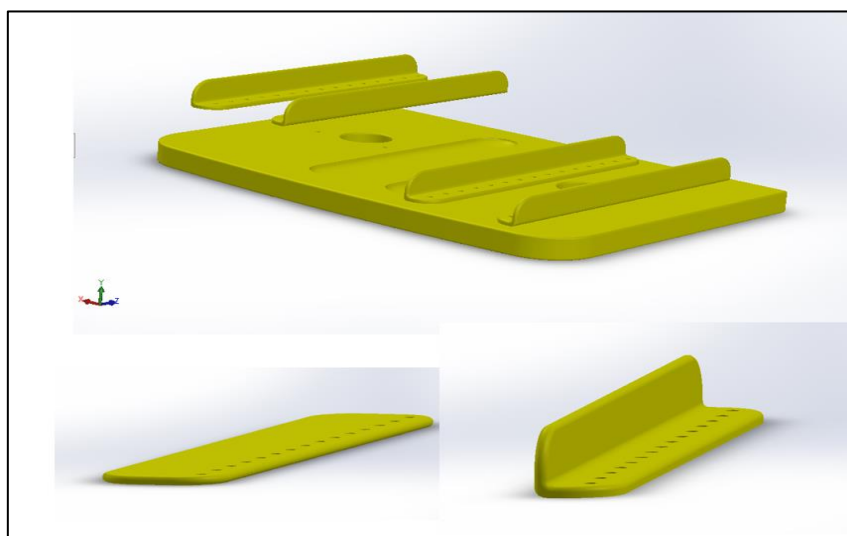


(IMS-Productivity.com, 2018).

AWJC PROCESS - PART DETAIL CAPABILITY		
PART DETAIL	CAPABILITY	
Profile	✓	
Hole	✓	
Rib	X	
Surface Finish	✓	
Recess	X	

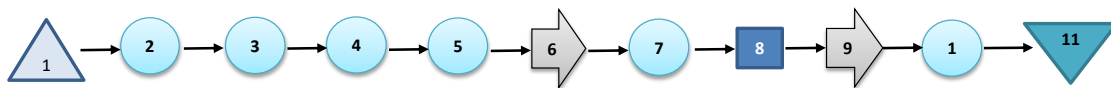
Initial analysis of the AWJC process determined fewer steps were required to manufacture the part than CNC Milling. However, Operation 8 is a requirement for a secondary fabrication process. The Part Detail Capability Table shows that the Abrasive Waterjet Cutting process would not be able to machine the Recess or the Rib detail. To mitigate this problem, a discussion regarding the requirement of the Recess with the customer could determine whether it is detrimental to the design; perhaps the feature is insignificant and can be eliminated. If the Recess cannot be eliminated from the design, then an additional Machining process would need to be added to the Work Flow Chart.

Operation 8 - The secondary fabrication proposed for the Rib detail consists of manufacturing additional components, which could be machined through AWJC, formed and then possible spot welded onto the main body of the component as illustrated below.



4.1.3 DMLS Process

DMLS Predicted Process Map (ASME).		Operation	Transport	Delay	Inspection	Store	Receive
No	Process Step						
1	CAD file/design						✓
2	STL Covert	✓					
3	File Transfer	✓					
4	Machine setup	✓					
5	Build	✓					
6	Remove and clean up		✓				
7	Post Process (Sand blasting, polishing, etc).	✓					
8	Inspection				✓		
9	Transport to Heat Treatment Pocess		✓				
10	Heat Treatment Process	✓					
11	Packaging and storage					✓	



(IMS-Productivity.com, 2018).

DMLS PROCESS - PART DETAIL CAPABILITY		
PART DETAIL	CAPABILITY	
Profile	✓	
Hole	✓	
Rib	✓	
Surface Finish	X	
Recess	✓	

The process map for DMLS is once again shorter and with fewer operations than CNC Milling. However, the Part Detail Capability table highlights this technology's poor surface finishing capabilities. A Post processing operation had to be added, which may require its own Work Flow Chart, therefore, introducing more time and overall cost into manufacture.

Research into DMLS has shown that there is potential to adjust the mechanical properties of a material during the build process (Brandt, 2017). Mahmud, et al., (2018) also states that no residual

stresses are present post build; which may eliminate the need for the post heat treatment operation specified by the customer. Unfortunately, more detail surrounding the heat treatment process is required to conclude on this possibility. Therefore, the Work Flow Charting illustrated that fewer process steps were required for CNC Milling, once you factored in the secondary fabrication required regarding AWJC and post processing regarding surface finish with DMLS.

4.2 Manufacturing System Technology Comparison Table

Variables	PROCESS TECHNOLOGY COMPARISON		
	Traditional	Non-Traditional	
	CNC Machining (Milling)	Abrasive Water Jet Cutting	Powder Bed Fusion - Direct Metal Laser Sintering
Process	Subtractive method - Process starts with a blank or solid block of material, rotary cutting tools remove material to the required contour.	Subtractive method - Process starts with a blank or solid block of material, and cuts final shape by erosion using high speed abrasive waterjet stream.	Parts are built by adding material one layer at a time. A laser is used to fuse metall powder together, layer by layer and a range of metals are available.
Surface finishing	Smooth surface finish generally requiring no further processing, or possible Light Media blasting with anti corrosive properties.	Usually none, AWJC is a cold cutting process that leaves a satin smooth edge. No heat effect zone	Rough stacked surface finish requiring machining, media blasting, sanding and polishing ot micro-polishing.
Material Limitations	Mostly used for machining metals. However, can also be used for machining plastics, acrylics, softwoods and hardwoods, modeling foams and machining wax. Metals with a hardness below Rockwell 45, some plastics and ceramics	Virtually any material	Aluminium, Stainless Steel, Titanium, Inconel
Maximum part size	4200 x 2250 x 800 mm (SMTCL-America Standard)	Industry standard equipment 60,000psi - 100mm in steel 94,000psi - 300mm thick alu, 130mm steel and 130mm carbon fibre composite. Generally - profiles are cut from flat material although it is possible to cut /trim 3D objects. The material size is dependant on the AWJC bed, sizes range from 737mm x 660mm to 14.2m x 4m. Material thicker than 75mm generally becomes less cost effective because of slower cutting speeds	1100 x 1100 x 300 mm build envelope by GE Additive's Project A.T.L.A.S (Additive Technology Large Area System). Previously 800 x 400 x 500 mm build envelope by GE Additive's X LINE 2000R
Accuracy	± 0.025 - 0.125 mm	± 0.025 mm for thicknesses up to 50mm, although ± 0.05 mm is perhaps more realistic in most cases.	± 0.100 mm
Machine Setup	CNC setup requires skilled operators, tool selection, spindle speed and cutting path must be considered. Build time is adversely effected by these factors. labor intensive, manual manipulation of the blank is required for positioning and alignment.	Same for all material, Fast and easy. The manufacturing process involves placing the part on the machine bed, generally no work holding clamps are required (except for 5 axis cutting). After machining, the components are ready for use or post-processing.	Operator prepares the digital file (chooses orientation and adds support), transport the file to the machine, where it is built with minimal intervention. No tooling or fixtures - initial setup costs are low. When part is complete, cleaning and post-processing is required, which is the most labour-intensive aspect of the 3D printing.
Capability	limitations - tool access and clearances, hold or mount points, as well as the inability to machine square corners due to tool geometry.	Markets mainly aimed at 3 axis machines and predominatly used for cutting 2D profiles. However, AWJC can be 7 axis, referred to as robotic waterjet cutting.	Strong complex parts, can be stacked in build volume. More cost effective with complex small parts.
Environmental	High waste, uses cutting oils and lubricants.	Low waste. Garnet and waste water is generally sent to landfill. However, if the material being machined is harmful (lead, beryllium, etc), both waste streams must be further processed to meet environmental legislation. Energy usage - 50 times more energy required for a saw cut of the same length and one-third that of a wire EDM, but the environmental impact is small and about the same as driving a car for the same amount of time.	Extremely low waste, excess powder can be recycled.
Safety	Most accidents occur in the same ways as at conventional machines - poor handling, metalworking fluids, and noise, but risks from: aerosol mists from metalworking fluids may be higher because of higher operating pressures and speeds, and noise, particularly from high-speed cutting (and especially from groups of machines operating together) may be higher.	Jet cutting is one of the safer cutting technologies, but you still need to take precautions to minimize the chances of or ill effects or an injury.	Fire and explosion risk from powdered metals such as titanium and aluminium. Powder inhalation & contact Inert Gas Asphyxiation
Strategic Gains	Flexibility for part developments: • Multiple program capability, • CNC controls tool path and is not reliant on tool shape. • Variable mass produced tooling available.	Flexibility for part development: • Cut any material • No heat effected zone • No thermal distortion from machining	Flexibility for part development: • 'First to market', Reduced leadtime from prototyping • Almost unrestricted potential for designers
Throughput	• Fast cycle times possible • Excellent repeatability • Multitasking operations	• Uneconomical on thick material because of slower cutting times • Multiple cutting head systems greatly increase throughput • More suited to difficult to cut material	• PBF is a relatively slow process and it can take days or even weeks to create large parts • Smaller parts can be nested within the build chamber to increase throughput.

(Alsoufi, 2017; Brandt, 2017; Claus, 2015; Mahmud, et al., 2018; Hse.gov.uk, 2019; E-Manufacturing.com, 2019; Kalil. 2019; Olsen, 2008; Varotsis, 2018; Liang and Shih, 2016).

4.3 Manufacturing System Selection Matrix

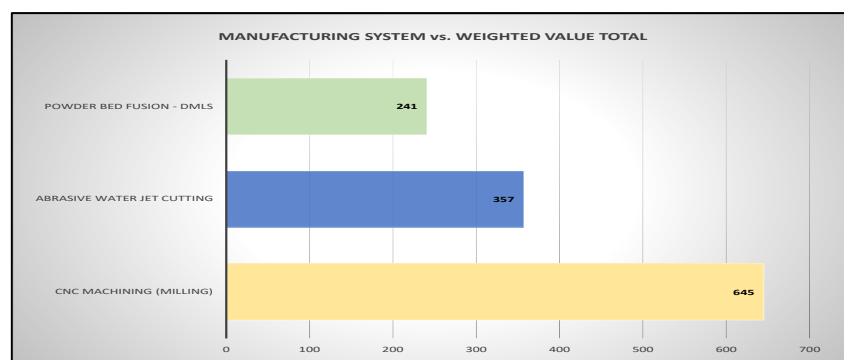
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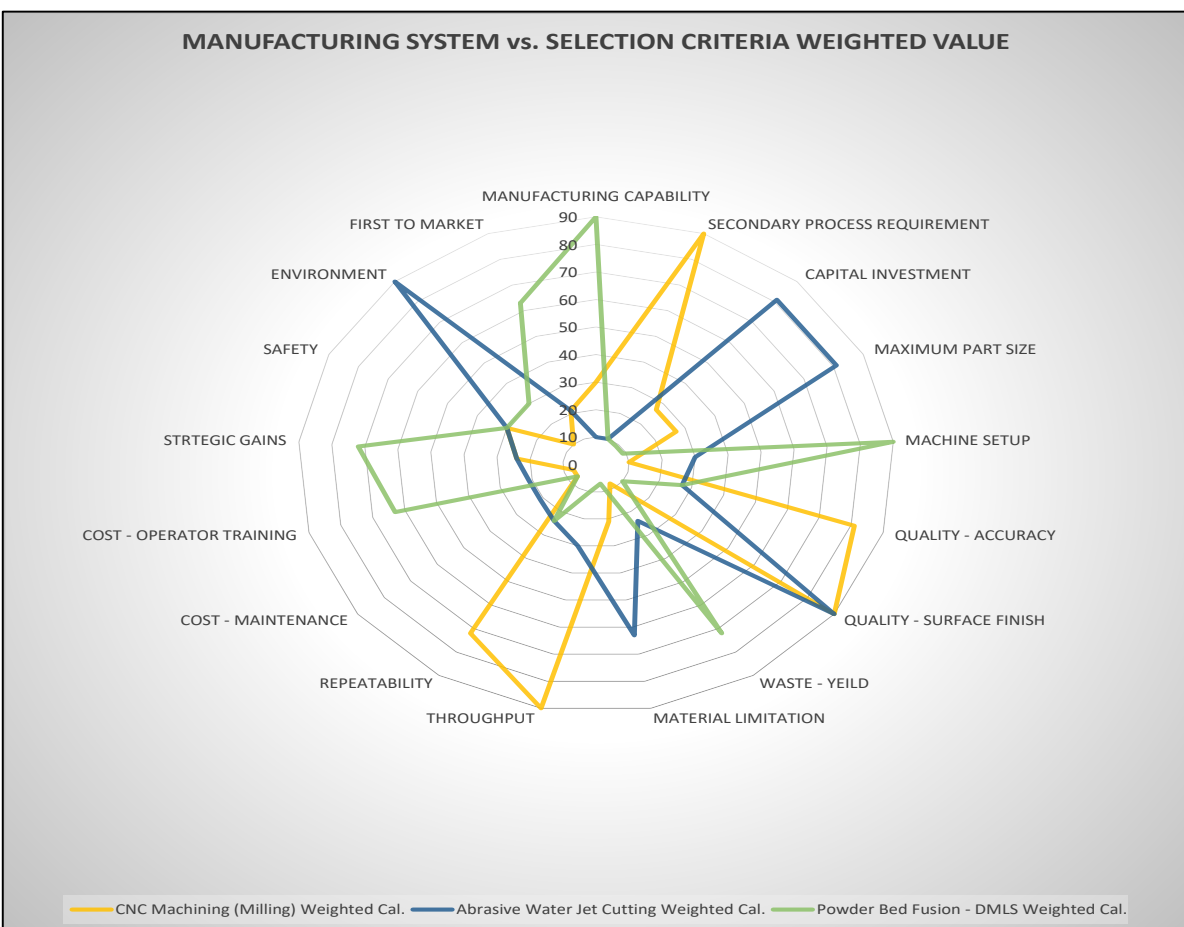
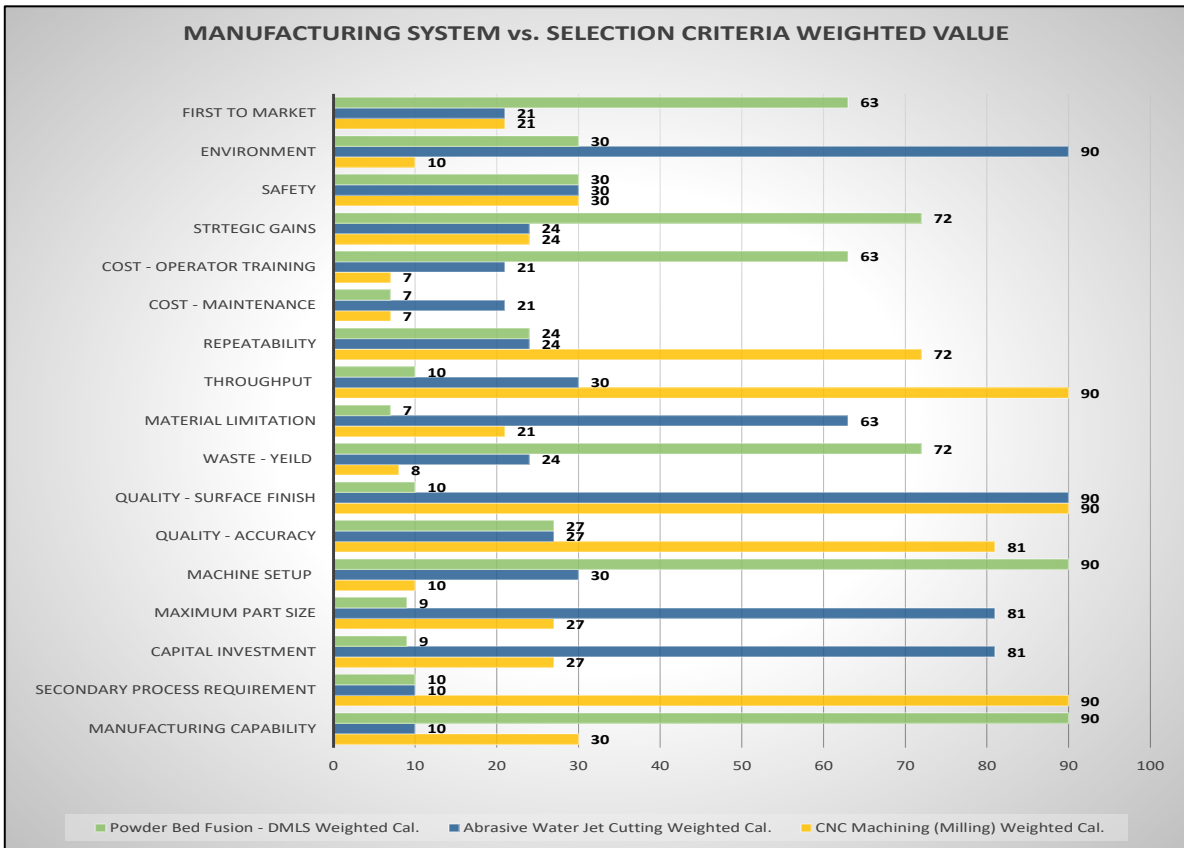
PROJECT OWNER: ANDREW CURTIS		DATE: 15/03/19		SELECTION CRITERIA																		
MANUFACTURING SYSTEM SELECTION MATRIX				SELECTION CRITERIA																		
				MANUFACTURING CAPABILITY	SECONDARY PROCESS REQUIREMENT			CAPITAL INVESTMENT	MAXIMUM PART SIZE	MACHINE SETUP	QUALITY - ACCURACY	QUALITY - SURFACE FINISH	WASTE - YIELD	MATERIAL LIMITATION	THROUGHPUT	REPEATABILITY	COST - MAINTENANCE	COST - OPERATOR TRAINING	STRATEGIC GAINS	SAFETY	ENVIRONMENT	FIRST TO MARKET
				WEIGHTING																		
MANUFACTURING SYSTEM				10	10	9	9	10	9	10	8	7	10	8	7	7	8	10	10	7	TOTAL	
CNC Machining (Milling)		Value	3	9	3	3	1	9	9	1	3	9	9	1	1	3	3	1	3	645		
		Weighted Cal.	30	90	27	27	10	81	90	8	21	90	72	7	7	24	30	10	21			
Abrasive Water Jet Cutting		Value	1	1	9	9	3	3	9	3	9	3	3	3	3	3	3	9	3	357		
		Weighted Cal.	10	10	81	81	30	27	90	24	63	30	24	21	21	24	30	90	21			
Powder Bed Fusion - DMLS		Value	9	1	1	1	9	3	1	9	1	1	3	1	9	9	3	3	9	241		
		Weighted Cal.	90	10	9	9	90	27	10	72	7	10	24	7	63	72	30	30	63			
		TOTAL	130	110	117	117	130	135	190	104	91	130	120	35	91	120	90	130	105			
												KEY		1 = Low 3 = Medium 9 = High								

(Sigmapro, 2018).

4.4 Graphical Analysis

As the bar chart illustrates below; CNC Milling was rated with the highest values based on the criteria established for this application. However, what must be recognised is that although CNC Milling scored the highest overall, both other processes scored higher than CNC Milling in certain criterions as can be seen from the further graphical analysis to follow.





5.0 Conclusion

To compare AWJC to CNC Milling has been very difficult throughout this review, as both technologies have strengths for different applications. Milling machines are far more flexible and can offer many additional multitasking operations along with profiling in a comparison with Abrasive Water Jet Cutting. If we were to consider both of these machines in only 2D cutting or profiling, then in many cases CNC Milling machines can generally cut faster. However, the setup, programming, tool changes, post clean up and fixture/clamping requirement for milling, greatly effects the total processing time for a part. For this reason, multi-head AWJC machines can outperform CNC Milling on throughput when dealing with 2D applications, especially on thinner material. Also, AWJC have virtually no limitations on the type of material which the technology can cut. Both processes are subtractive but AWJC only has a very narrow jet reducing the amount of waste generated throughout the process. When considering 3D applications CNC Milling offers six axis machining at absolute precision. Robotic waterjet cutting in comparison reintroduces many of the additional setup, clamping and programming constraints earlier referred to regarding CNC Milling, although unfortunately wont deliver on precision, roundness and surface finish.

On comparison between DMLS and CNC Milling the first factor to consider would be part size capability. The vast majorly of DMLS machines available have a relatively small build chamber. Therefore, the size of the component can eliminate this technology altogether. The greater the height and larger the part volume will directly increase the build time and the cost. However, as this technology becomes more popular with more demand, the build chamber size is increasing. DMLS parts offer designers almost unlimited freedom, parts can be built with complex internal or lattice structures, which would be impossible to machine on a CNC Milling machine. The increased complexity does have its limitations. Post processing operations are often required to remove support structures, improve surface finishes and details such as seal grooves, threads, bores or fits will require machining especially if roundness is critical. In most cases this is not a requirement on CNC Milling and interfaces do not require additional consideration. When considering cost effectiveness in regard to quantities with these two processes the fundamentals are very difficult to summarise. CNC Milling programming time increases with increased component complexity, although this can be offset with large batch sizes and economies of scale. With regard to the DMLS process, quantity is linked to how many parts that can be packed onto the build platform. Therefore, the smaller the part the more likely DMLS can offer a cost-effective solution.

The process evaluation, literature review and quantitative analysis all would suggest that the organisation's current traditional method of manufacturing this part through CNC Milling is the most efficient and cost effective. This should not however reflect or suggest that CNC Milling is a better

process for all applications. What has become evident throughout this project is the strengths and weaknesses of each technology, and how each process can be complimented by one another. Abrasive waterjet cutting is often used for bulk material removal before CNC Milling, or CNC Milling can be used to provide added precision to complex DMLS parts. If the technology review had been considering a different part, with different requirements, then either of the other two technologies could have been valued differently.

The advice I would present to the Organisation, based on the academic research and analysis completed within this technology review, would be that DMLS technology is not quite ready to manufacture this part economically. However, I believe there is value in further analysis into the feasibility of introducing a three-axis abrasive waterjet cutting machine, as a pre-process bulk material removal operation prior to CNC Machining.

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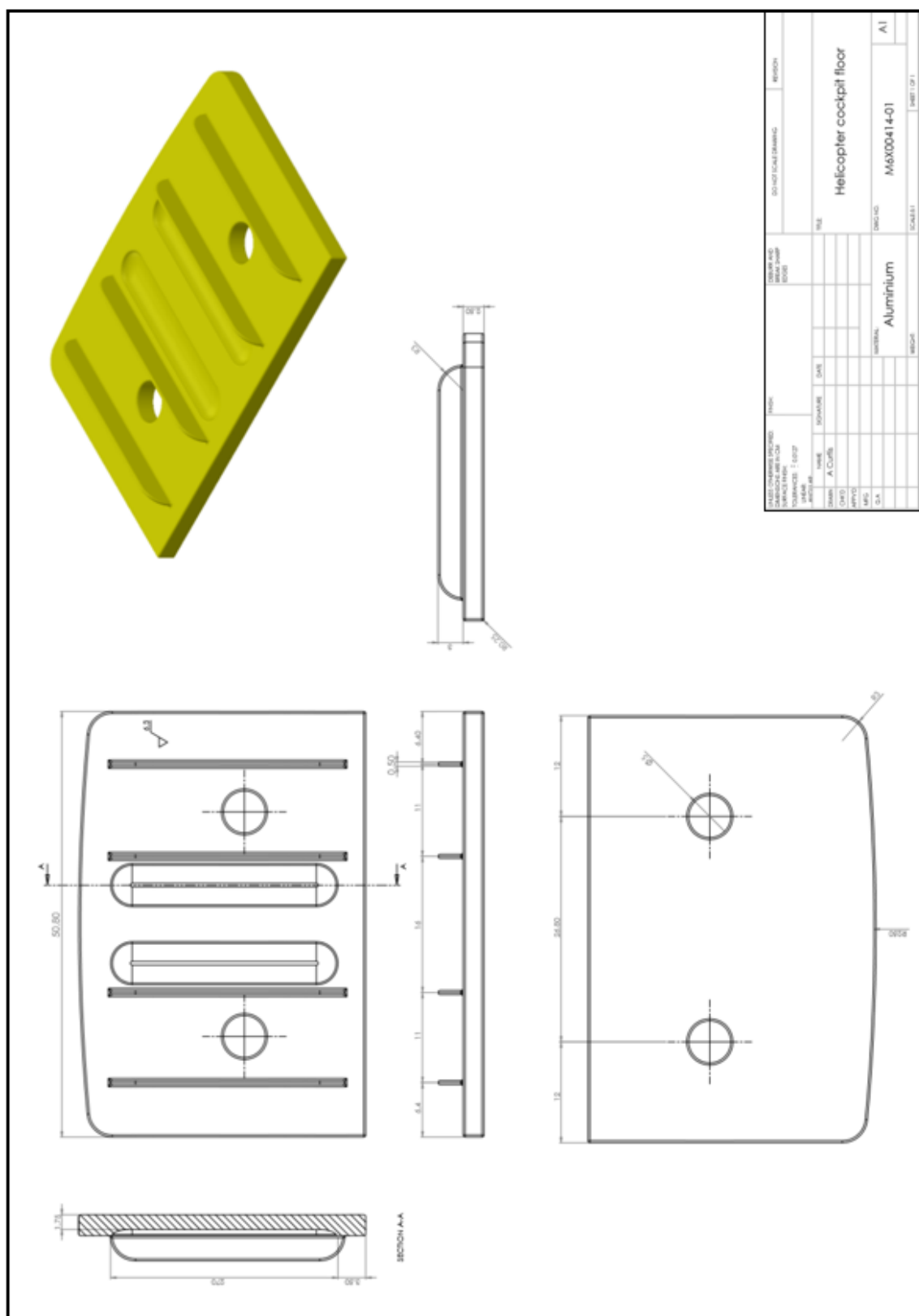
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Appendix A: Drawing No. M6X414-01



Appendix B. Surface Finish Chart

MICROMETERS RATING	MICROINCHES RATING	APPLICATION
25/ ▽	1000/ ▽	Rough, low grade surface resulting from sand casting, torch or saw cutting, chipping, or rough forging. Machine operations are not required because appearance is not objectionable. This surface, rarely specified, is suitable for unmachined clearance areas on rough construction items.
12.5/ ▽	500/ ▽	Rough, low grade surface resulting from heavy cuts and coarse feeds in milling, turning, shaping, boring, and rough filing, disc grinding and snagging. It is suitable for clearance areas on machinery, jigs, and fixtures. Sand casting or rough forging produces this surface.
6.3/ ▽	250/ ▽	Coarse production surface, for unimportant clearance and cleanup operation, resulting from coarse surface grind, rough file, disc grind, rapid feeds in turning, milling, shaping, drilling, boring, grinding, etc., where tool marks are not objectionable. The natural surfaces of forgings, permanent mold castings, extrusions, and rolled surfaces also produce this roughness. It can be produced economically and is used on parts where stress requirements, appearance, and conditions of operations and design permit.
3.2/ ▽	125/ ▽	The roughest surface recommended for parts subject to loads, vibration, and high stress. It is also permitted for bearing surfaces when motion is slow and loads light or infrequent. It is a medium commercial machine finish produced by relatively high speeds and fine feeds taking light cuts with sharp tools. It may be economically produced on lathes, milling machines, shapers, grinders, etc., or on permanent mold castings, die castings, extrusion, and rolled surfaces.
1.6/ ▽	63/ ▽	A good machine finish produced under controlled conditions using relatively high speeds and fine feeds to take light cuts with sharp cuttings. It may be specified for close fits and used for all stressed parts, except fast rotating shafts, axles, and parts subject to severe vibration or extreme tension. It is satisfactory for bearing surfaces when motion is slow and loads light or infrequent. It may also be obtained on extrusions, rolled surfaces, die castings and permanent mold casting when rigidly controlled.
0.8/ ▽	32/ ▽	A high-grade machine finish requiring close control when produced by lathes, shapers, milling machines, etc., but relatively easy to produced by centerless, cylindrical, or surface grinders. Also, extruding, rolling or die casting may produce a comparable surface when rigidly controlled. This surface may be specified in parts where stress concentration is present. It is used for bearings when motion is not continuous and loads are light. When finer finishes are specified, production costs rise rapidly; therefore, such finishes must be analyzed carefully.
0.4/ ▽	16/ ▽	A high quality surface produced by fine cylindrical grinding, emery buffing, coarse honing, or lapping, it is specified where smoothness is of primary importance, such as rapidly rotating shaft bearings, heavily loaded bearing and extreme tension members.
0.2/ ▽	8/ ▽	A fine surface produced by honing, lapping, or buffing. It is specified where packings and rings must slide across the direction of the surface grain, maintaining or withstanding pressures, or for interior honed surface of hydraulic cylinders. It may also be required in precision gauges and instrument work, or sensitive valve surfaces, or on rapidly rotating shafts and on bearings where lubrication is not dependable.
0.1/ ▽	4/ ▽	A costly refined surface produced by honing, lapping and buffing. It is specified only when the design requirements make it mandatory. It is required in instrument work, gauge work, and where packing and rings must slide across the direction of surface grain such as on chrome plated piston rods, etc. where lubrication is not dependable.
0.05/ ▽ 0.025/ ▽	2/ ▽ 1/ ▽	Costly refined surfaces produced by only the finest of modern honing, lapping, buffing, and superfinishing equipment. These surfaces may have a satin or highly polished appearance depending on the finishing operation and material. These surfaces are specified only when design requirements make it mandatory. They are specified on fine or sensitive instrument parts or other laboratory items, and certain gauge surfaces, such as precision gauge blocks.

(Cnccookbook.com, 2018).