PARAMETER SELECTION APPROACH AND OPTIMIZATION IN ABRASIVE WATER JET MACHINING

by

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Abstract

Abrasive Water Jet Machining (AWJM) is a non-traditional machining technique that uses high pressurized water for production. It is advantageous in comparison to conventional milling in terms of being cost, time and environmentally effective. For this to be the case, parameters must be chosen accordingly. Since AWJM has been in use for over decades, a significant amount of research has been made of parameter effects on mainly obtaining the best surface quality and maximum material removal rate.

This thesis proposes a parameter selection approach, taking the interrelations among the parameters that affect the process. By looking at the relations, a method is proposed to choose parameters within specific ranges. The most effective parameters are abrasive flow rate, pressure and feed rate, whereas stand-off distance can be taken as minimum in general. The proposed approach gives an insight into parameter relations, in addition to guiding the parameter selection order.

Minimum cycle time and minimum total cost are also computed through different solvers. In this research, FMINCON solver of MATLAB © and Genetic Algorithm are used. Both time and cost are computed by the mentioned optimization techniques and compared in terms of their result. It is seen that both methods have similar results, however the randomness in genetic algorithm, FMINCON solver is preferred in this case.

Flatness, perpendicularity and roundness features of parts that AWJM produced are also examined. It is concluded that abrasive water jet machining is capable of achieving part quality within the tolerance values for these features.

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Anahtar Kelimeler: parametre seçimi, aşındırıcı su jetinde optimizasyon, genetik algoritma, parametre optimizasyonu, maliyet ve zaman minimizasyonu

Özet

Aşındırıcı su jeti, üretimde yüksek basınçlı su kullanan ve geleneksel olmayan bir imalat metodudur. Geleneksel frezeleme ile kıyaslandığında maliyet, zaman ve çevre açısından daha avantajlıdır. Bunun olması için parametrelerin doğru şekilde seçilmesi gerekir. Aşındırıcı su jeti uzun yıllardır kullanılan bir yöntem olduğundan, literatürde parametrelerin yüzey kalitesine ve talaş kaldırma miktarına olan etkisini anlatan birçok araştırma vardır.

Bu çalışmanın odak noktası parametreler arasındaki ve parametrelerin prosesler üzerindeki etkiyi göz önünde bulundurarak bir parametre seçim yöntemi önermek. Parametreler arasındaki ilişkiye bakarak, parametreleri belirli aralıklarda seçmek üzere bir metot önerilmiştir. En etkili parametrenin aşındırıcı parçacık akış oranı, basınç ve hız iken, duruş mesafesi genel durumlarda minimum değer alınabilir. Önerilen bu yöntem parametreler arasındaki ilişkiyi gösterdiği gibi, parametre seçiminde sıralamaya da önem vermektedir.

Minimum iş çevrim süresi ve maliyet farklı algoritmalar tarafından çözdürülmüştür. Bu çalışmada FMINCON çözümcüsü ve Genetik Algoritma kullanılmıştır. Zaman ve maliyet, belirtilen iki optimizasyon tekniği ile hesaplanmış ve sonuçları karşılaştırılmıştır. Her iki algoritma birbirine yakın sonuçlar vermesine rağmen genetik algoritmadaki rastgelelikten dolayı, FMINCON çözümleyicisi tercih edilmiştir.

Aşındırıcı su jeti tarafından işlenen parçalarda düzlemsellik, diklik ve dairesellik incelenmiştir. Bunun sonucunda aşındırıcı su jetinin verilen tolerans dahilinde belirtilen özellikleri gösteren parça işleyebildiği teyit edilmiştir.

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LIST OF ABBREVIATIONS

ABC	Artificial Bee Colony
ANN	Artificial Neural Network
ANOVA	Analysis of Variance
AWJ	Abrasive Water Jet
AWJM	Abrasive Water Jet Machining
CS	Cuckoo Search
DoE	Design of Experiment
FL	Fuzzy Logic
GA	Genetic Algorithm
GRA	Grey Relational Analysis
MRR	Material Removal Rate
RSM	Response Surface Methodology
SA	Simulated Annealing
SAO	Sequential Approximation Optimization
SOD	Stand-off Distance
TLBO	Teaching Learning Based Optimization

CHAPTER 1

Introduction

AWJM is a machining method that has gained more importance in past decades especially in machining of difficult-to-cut materials given that the process meets the quality expectations and obeys the geometrical constraints. Due to the fact that it is cost and time efficient as well as being environmentally friendly, AWJM is a choice over conventional machining. Background information, as well as the related research in this field, are given in this chapter. It can be seen that, especially effects of parameters are a well-studied area in literature. The thesis objective is also mentioned, aiming to minimize the cycle time and total cost on a given process while meeting the constraints of each parameter.

1.1 Background

Any sort of machining operations goal is to obtain a maximized material removal rate, while having the lowest cost and energy consumption possible. Abrasive water jet machining has been present in machining field in manufacturing for over decades. It is a non-conventional machining technique that works with high pressure water in order to obtain high velocity in combination with abrasive particles in order to machine all kinds of different materials [1].

AWJM is widely used, and this is due to the advantages it has over conventional machining. Firstly, AWJM can be used for any material, although the advantage comes from especially being used for difficult-to-cut materials that may be very soft, brittle or ductile. Metal matrix composites, titanium aluminides, nickel-based alloys, ceramics, ceramic matrix composites are examples of difficult-to-cut materials [2]. In addition to this, AWJM does not generate heat like conventional machining does, allowing thick materials to be machined at a single pass.

Since the AWJ uses high pressure water and abrasive particles, it is environmentally neutral, meaning that the energy consumption is lower than conventional machining. In addition to being environmentally friendly, it does not cause chatter; hence it is not as sensitive as conventional milling to material properties [1]. Compared to conventional machining, AWJM does not require various tools. All sorts of shapes and geometries can be achieved by one tool. This allows AWJM to be an attractive option for prototyping since most shapes and materials can be cut with it.

A major drawback of AWJM would be the lack of dimensional accuracy. Due to the fact that AWJM is done by pressurized water and abrasive particles, it is not very likely to achieve the highest accuracy. Therefore, multiple layer cutting does not always result in the perfect surface quality. Hence, it is safe to say that AWJ is utilized the best when single layer machining is done. In addition to this, it causes loud noise and a cluttered environment for work.

Considering the advantages and disadvantages, it is safe to say that AWJM can be used for most operations. It is a cost-effective way to achieve high cutting performance. However, some parameters need to be taken into consideration. These parameters can be stated as follows; water flow rate and nozzle diameter, stand-off-distance, abrasive flow rate, abrasive particle size, water jet pressure abrasive type and traverse rate. These parameters go hand-in-hand when achieving a depth of cut. However, these parameters have their constraints. It is not possible to set parameter values as the user requires. Each of them has its limits, and certain values need to go together to achieve the intended cutting depth.

1.2 Objective of the Thesis

Main goal of the research in this thesis is to develop a parameter selection approach for AWJM, which gives a parameter selection process in order to find the optimum values for the process itself in terms of cycle time and cost. Therefore, it is important to identify constraints that will construct the method that the process will be optimized. Different parameters lead to different results. These results also differ depending on the geometry of the part. Clearly, there are drawbacks in such processes, which the biggest one might not achieve the intended surface roughness. Depending on single or multi-level machining, parts will differ in terms of their surface quality. Therefore, AWJM may be suitable only for roughing operations. In most cases, due to its advantages, AWJM may be even more beneficial than conventional milling, such as no heat generation during the process, not needing different tools for each operation, being able to cut difficult-to-cut materials.

The intended result should be within the limit of each constraint. It is essential to select each parameter in its limits since going over or being under the limit may cause unintended results. The model that shall be developed aims to cover parameter limits, whereas looking for the minimum cost and time spent in order to complete the process, regardless of its geometry and material. The goal is to obtain maximized material removal rate at the lowest cost and cycle time possible.

1.3 Literature Review

In literature, there have been various research on optimizing the process parameters. Different studies propose different objective functions and optimization techniques. This study aims to present an approach that leads to the presented techniques in the literature to find the optimized values for process parameters. After going through the literature, it is possible to claim that surface roughness and material removal rate are the two most common objectives that are focused on. An approach or an optimization technique is necessary to obtain optimized results since in general, AWJM parameter selection may be based on experience. Hence, different studies with different methods will be presented.

1.3.1 Parameter Optimization for Maximized MRR

Jain et al.[3] developed an optimization model where the decision variables are set as the nozzle diameter, mass flow rate of water , traverse speed, pressure and mass flow rate of the abrasives. This study focused on maximizing the material removal rate while constraining all the decision parameters and power consumption. Since this is a non-linear programming model and conventional optimization techniques fail to solve such problems, the Genetic Algorithm (GA) was found to be the most powerful tool for optimization to be used. There is no general algorithm for this type of optimization. Hence the most influential parameters were determined, and their combinations were obtained where each combination was run at a certain amount. Therefore, the solution with the best numerical value in terms of the constraints and the objective function, was chosen to be the optimized solution. It is seen that MRR increases with the nozzle diameter and traverse speed while becoming steady after a certain value. In contrast, the solution is not dependent on the power consumption constraint.

Parikh and Lam [4] touched on a neural network approach since previously done models may not be applicable for all types of operating conditions. In this paper, two ANN approaches were proposed. One method used the input and output data to train weights on the data by a repetitive process. The second approach was based on training the data. In addition to neural network approaches, linear and non-linear regression models were used to evaluate the performance. With the significance level of 0.05, it was concluded that the linear regression model did not perform well, indicating the fact that linearity is not the case for AWJM parameters. Even though the non-linear regression model performed better than the linear regression model, ANN approaches provided better results.

It was observed that there were teaching learning-based optimization (TLBO) algorithms used in process parameter optimization. One would be Pawar and Rao [5], which compared the TLBO to other optimization algorithms. This algorithm is based on replicating the teaching and learning behaviour of the teacher and learner in a specific environment. After running the algorithm for several times, the result obtained was compared to the results observed from simulated annealing and genetic algorithm. It was concluded as the TLBO results surpassed GA and SA observations in terms of accuracy of the results.

Further research on achieving the material removal rate was done by Yue et al. [6]. Response surface methodology was the technique that was used in this study. Optimum process parameters were found by associating the RSM model with sequential approximation optimization (SAO) from material removal rate and surface quality. As a result, it was observed that the material removal rate is affected the most by pressure and then the abrasive flow rate. In addition to this, it is possible to achieve a higher material removal rate by not worsening the surface quality.

1.3.2 Parameter Optimization for Minimized Surface Roughness

Another primary goal to optimize in literature was the surface roughness. Many researchers focused on finding the optimal parameters by trying different algorithms in order to have the best surface quality. To minimize the surface roughness, Zain et al. [7] computed process parameters of stand-off distance, abrasive flow rate, traverse speed, water pressure and abrasive grit size by genetic algorithm and simulated annealing and compared the results with experimental data. The study showed that the algorithms used were successful in competing for the optimum parameters for minimum surface roughness. Liu et al.[8] also focused on surface roughness in addition to finding the optimum values for depth of cut. To achieve this, response surface methodology was used. RSM constantly optimized the fundamental parameters for both surface roughness and depth of cut. After the predicted and experimental results are compared, it was observed that the error rate was not high. Hence RSM is an acceptable way of optimizing surface roughness and depth of cut. Taking the previous research done, Yusup et al.[9] worked with the artificial bee colony (ABC) algorithm in order to optimize parameters for good surface quality since ABC has less computation time. This method was compared to ANN, GA, and SA. The obtained results in terms of surface roughness were compared to experimental results and previously mentioned optimization algorithms. It was concluded that ABC outperformed the rest of the techniques.

Mohammed et al.[10] had a study on finding the best surface roughness with cuckoo search (CS). This method managed to give more accurate results than ANN. Hence it was concluded that CS can provide the minimum surface roughness as a result. Bhowmik and Ray [11] brought surface roughness prediction into attention sustainable manufacturing by using fuzzy logic (FL). In this study, green composites were used. As previous research, FL surface roughness optimization aligns with experimental results. The database is gathered by Taguchi L_{27} array. In addition to this study, Santhanakumar et al.[12] used the same method to form the database. However, in this study, grey-based response surface methodology was used, similar to Bhowmik and Ray [13] that also used response surface methodology in their studies. This study focused on obtaining an optimized surface roughness as well as minimizing the process time. ANOVA corroborated both of the studies in order to find the parameter effects on the objective function and to improve the method for optimization. As a result, both studies concluded that it is possible to use response surface methodology to predict an optimized surface quality value. One part of Mellal and Williams' [14] research focused on minimizing the surface roughness value. Hoopoe heuristics and cuckoo algorithm were compared to other techniques in the literature. It was observed that they outperformed many different techniques. Hoopoe heuristic had similar results with ANN, although ANN required further functional computations. The cuckoo algorithm outperformed all other algorithms besides the artificial bee colony technique [9].

Another common approach that Perec et al.[15] also focused on parameter optimization with means of the mathematical model. The objective function was to minimize the surface roughness, where the best parameters for the objective were selected by the Taguchi method. It was concluded that pressure is the most and traverse speed is decided to have the least effect on surface roughness. Taguchi was found to be an appropriate method to predict the optimal parameters since the experiment, and the model results were consistent. It is also possible to research combination Taguchi and Grey Relational Analysis in studying the optimized process parameters in terms of high material removal rate and low surface roughness. Viswanath et al. [16] supported this research by optimizing the process parameters by Taguchi and ANOVA. However, the difference in this study is that the material was Inconel 625. It was confirmed that surface roughness and material removal rate are mainly affected by pressure, abrasive flow rate, feed rate and stand-off distance. Muthuramalingam et al. [17] also investigated the process parameters by the Taguchi method. The observed results coincide with Viswanath et al.[16], wherein this study, the optimal values for the process parameters were also obtained. It is important to note that stand-off distance was found to greatly impact the energy of the AWJM process. A very similar experiment was done by Nagdeve et al. [18], and used Taguchi to obtain the optimized outputs. The result turned out to be as expected and matched up with both Viswanath et al. and Muthuramalingam et al., Kuila and Bose [19] focused on finding the impact of parameters on the previously mentioned outputs. The design of the experiment was L9 orthogonal array in order to prepare the inputs, where the Grey Relational Analysis computed the optimized results. As a result, it was found that the feed rate has approximately 60% contribution to the surface quality. In contrast, the contribution to material removal rate is at much higher rates which are around 95%. Grey Relational Analysis gave the best optimized output values and proved that the process parameter values chosen by this method improved both surface quality and the material removal rate.

It is also possible to estimate the surface roughness as Deris et al. [20] have done in their studies. In this research, support vector machine and grey relational analysis were used as a hybrid method. As the first step, the main parameters' values of the AWJM process were determined and analysed by the grey relational analysis method. The hybrid model of the two methods was used in order to predict the surface quality. It was seen that this hybrid method was more efficient in comparison to the regular support vector machine method since it is possible to eliminate unnecessary data and features.

1.3.3 Parameter Effects on Features

In addition to all the previously mentioned optimization techniques, it is essential to identify the relations among parameters and how much each parameter affects the objective function, where the main focus is on depth of cut. There has been much literature regarding investigating the effect of different parameters on surface roughness, depth of cut and material removal rate. Iqbal et al. [21] studied the impact of main AWJM parameters on the surface quality of the wear area. The results of the parameters were determined by ANOVA, where feed rate was found to be the most dominant parameter. In addition to this, surface quality may worsen in the cutting wear area if the abrasive flow rate decreases while feed rate is being increased. One other conclusion was that once the pressure and feed rate are increased, the width of cut shall be reduced.

Arola and Hall [22] studied the parameter effects on surface roughness, particle distribution and particle concentration and on the test specimens. The highest surface roughness was observed at the highest pressure and abrasive flow rates. It was also found that the highest abrasive concentration is achieved when the abrasive particle size is the grandest, and the impingement angle is expected. Lastly, the material removal rate is increased by the kinetic energy caused by the velocity of the abrasive particles. In the studies of D.V.Srikanth et al. [23], the parameter effects on material removal rate and surface finished were discussed. It was found that one of the most influential parameters is the stand-off distance, in addition to nozzle orifice diameter, nozzle angle, impingement angle. However, these parameters affect the objective function significantly less than the main four parameters: pressure, abrasive flow rate, SOD and traverse speed. It is possible to say that more extensive parameters are better for material removal rate, whereas smaller values for parameters are better for the kerf. Therefore, after ranking the parameters, it was observed that higher values for nozzle diameter, pressure, and SOD are more suitable for MRR, lower values are for the surface finish of the kerf. In a similar study, Ray and Paul [24] focused on the effect of main process parameters on MRR. It was found that an increase in pressure, nozzle diameter, and abrasive grain size led to an increased MRR. In addition to this, there was a new suggested term in this study, such as the material removal factor. This factor states that as this value decreases, it is mainly caused by high pressure. This leads to the fact that the amount of material removed per abrasive particle gram is higher at lower pressure. Hence, more material is removed at higher pressure due to the fact that the collision of particles at high pressure causes a decrease in kinetic energy.

Kulisz et al. [25] had similar research in terms of determining the parameters that affect the surface roughness to the greatest extend. In this study, there was not a direct correlation detected between the surface roughness and abrasive flow rate. However, it was observed that when the abrasive flow rate was at its maximum limit, the surface roughness was inclined to be at a lower value. Mentioning this, it is important to note that surface roughness had a more direct relationship with feed rate, tan abrasive flow rate. In addition to this, it was concluded that ANN is a beneficial tool in order to have predictive results with surface roughness. Moreover, Yuyong et al. [26] suggested having control over the main parameters of the process by ANN. It was found that the relationship between the surface quality and individual parameters is not linear. Therefore, this was concluded as controlling the surface roughness may be indirectly affected by the process parameters, especially the feed rate. However, the authors point out the fact that the dataset and the material used in this study were specific to this research and the setup; hence the result may vary at different datasets.

Aydin et al. [27] focused on the parameters that affect surface roughness by using Taguchi and ANOVA. It should be noted that the material used in this research is granite. After obtaining a DoE by Taguchi and analysing the results by ANOVA, it was concluded that pressure and abrasive flow rate are the process parameter that affects the surface quality at the greatest extend. The second most influential parameter was stand-off distance, followed by feed rate. These were the results obtained while disregarding the abrasive particle size. The conclusion about particle size was that as the particles tend to get larger, surface quality deteriorates. Hence, for better surface quality, smaller abrasive particles should be in use. The study by Azmir and Ahsan [28] supports the results that Aydin et al. [27] concluded. In addition to this, in order to improve the taper ratio and surface quality, abrasive flow and pressure rate shall be increased, whereas feed rate and the stand-off distance may be considered to be decreased in comparison to the firstly mentioned parameters. It was also observed that the tool orientation does not significantly improve neither the surface quality nor the taper ratio. Hocheng and Chang [29] investigated kerf generation on a ceramic plate. It was found that kerf width enhances as any of the main process parameters increase. Their study also claims that the taper ratio has a proportionate relationship with feed rate and abrasive grain size, whereas it has an inverse proportionate relation with pressure. It is important to note down that abrasive flow rate does not influence taper ratio.

Gupta et al. [30] studied the effect of parameters on the kerf width. This was done by ANOVA. It was found that at high feed rates, the kerf width is affected negatively since at fast speed there are a smaller number of abrasive particles to penetrate the surface which prevents the kerf width to be large. After the results being interpreted, it was found that the traverse speed has the most significant effect on the top of the kerf width, which is followed by water pressure. Kerf taper angle was also one of the studied outputs. This also resulted in the same parameters that have the most significant effect; traverse speed followed by the water pressure. It was observed that the kerf taper angle was at its lowest at the lowest traverse speed and pressure values. Another study on kerf characteristics is done by Wang and Wong [31], where the effect of pressure, feed rate, abrasive flow rate and stand-off distance were examined. Pressure and stand-off distance have a proportionate increase with both the bottom and top of the kerf width, meaning that kerf width also increases. Feed rate has an inverse proportion to the kerf width, meaning that an increase in feed rate results in a decrease in the kerf width, both on the bottom and top. This study also confirmed the fact that there is an inverse proportion between the surface roughness and the abrasive flow rate. Kumar and Kant [32] focused on the effects of the four main parameters on the kerf taper. In order to observe this, response surface methodology was used to systemize the experiments. The vision measurement system is used in order to obtain the taper of the kerf. As a result, feed rate and pressure were the two parameters that had the most effect on kerf taper. Also, at decreased feed rate and increased pressure, kerf taper would result in a decrease. Hence, it was possible to develop a predictive model in order to predict a taper angle in the light of specific process parameters. Therefore, it is possible to predict a minimized value for the kerf taper.

Hashish [33] focused on the parameters that affect the surface quality, such as taper angle, surface waviness, and burr height. It was concluded that surface waviness is an inevitable issue with any robot that has a jet. In addition to this, it is crucial to have the main four parameters steady. It was observed that traverse speed is the most sensitive among these parameters. The size of the abrasive particle mainly causes surface roughness and burr occurrence; hence parameters shall be selected cautiously. Lastly, kerf taper angle can be controlled by the material type, whether the machinability is high or not and depth of cut also has an important role in determining the taper angle. In further studies of Hashish [34], the effect of pressure was focused on. It was concluded that, the hydraulic efficiency tends to decrease at high pressure rates whereas nozzle and mixing tube wear and the need for maintenance increases. It is also important to note a linear relationship between the depth of cut and pressure. However, this linearity is valid until the threshold value for pressure. The values of other parameters set this threshold.

Shanmugam et al. [35] also focused on surface roughness and taper angle. Surface response methodology and ANOVA were used in order to design the experiments, where the results were found to be as feed rate and pressure having the most influence on both outputs. An interesting observation was that feed rate and stand-off distance reduction results in an increased value at both outputs. Hence, it was concluded that especially feed rate has an inverse proportion with both surface roughness and taper angle. Another study that supports this research belongs to Dumbhare et al. [36], where the effect of feed rate, abrasive flow rate and stand-off distance are investigated on surface roughness and taper angle. Since pressure is not consideration, feed rate was found to have the most impact on the aforementioned outputs. Stand-off distance and the abrasive flow rate have the most significant impact, consecutively after feed rate. Once these were determined, surface response methodology was used to find the optimal values for the process parameters.

As of a different perspective, Chakravarthy and Babu [37] focused on finding the optimal values for process parameters in order to optimize the value for depth of cut. In addition to previous research that has focused on the relationship among parameter and their effect on depth of cut, this study targeted the optimal depth of cut by applying fuzzy logic and genetic algorithm to select the parameters of the process. Different batches of parameters was determined by these methods, which were then applied multi-criteria optimization. This allowed the process to have a minimized cost while increasing production.

Jegeraj and Babu [38] have focused on the focusing and orifice nozzle diameter instead of the effects of main process parameters. In addition to the main process parameters, it is also important to choose the optimal values for the orifice and focusing nozzle diameter. Selvan et al. [39] conducted a study on parameter effects on depth of cut, where the focus was the effect of main four parameters. The experiments were done on phosphate glass; however, the results were compatible with previous experiments that were done on aluminium. It was found that the effect of abrasive flow rate and pressure parameters on the depth of cut did not differ a significant amount from each other. It was also concluded that the stand-off distance must be chosen as minimum as possible in order to obtain the intended kerf depth. As previously mentioned in other studies, traverse speed is found to have an inverse proportion with the depth of cut.

It is also essential to note down the effect of the type of different abrasive material. Khan and Haque [40] focused on different types of abrasive grains on AWJM processes. The abrasive materials that were used in this study are garnet, aluminium oxide, and silicon carbide. It should be noted that this experiment was done on the glass. At abrasive materials with higher hardness levels, the kerf depth may increase. The hardest material among the different types that were previously mentioned is silicon carbide. The comparison among the abrasives are made based on the taper. The variables in this experiment were feed rate, pressure, and stand-off distance. The taper is the lowest at the hardest material which is silicon carbide and highest at garnet. As previously mentioned, pressure has an inverse proportion with taper whereas stand-off distance results were seen to be proportionate. Kusnurkar and Sidhu [41], compared different types of abrasive materials similar to the previous study. In this paper, white aluminium oxide, brown fused alumina and garnet were considered, where the input parameters are stand-off distance and feed rate. The effect of these abrasive materials were observed on material removal rate, kerf taper and surface quality. In terms of surface roughness and material removal rate, it was observed that white aluminium oxide resulted as the most effective abrasive particle type. This was followed by brown fused alumina and garnet. It was also noted that in the industry garnet is the most common abrasive type. However, by replacing garnet with white aluminium oxide higher material removal rate and a better surface quality can be achieved. Kumaran et al. [42] took different abrasive materials to another perspective and compared different grain sizes, 80 and 120 mesh. The input and output variables are the same as the previously mentioned study. It was found that 80 mesh material resulted in decent surface quality in addition to a low kerf angle, whereas 120 mesh material had a more significant impact on the material removal rate.

In order to have a generalized point of view, Shah, and Patel [43] did a review on AWJM. It is possible to conclude that four main process parameters have the highest impact on the processes. Even though both abrasive flow rate and feed rate have an effect on material removal rate, it is possible to say that feed rate has a more significant effect. However, the feed rate cannot be maximized in every case since kerf formation also increases as feed rate enhances. Therefore, it is important to determine the feed rate value, taking the kerf formation, surface quality and material removal rate into consideration since this parameter is the variable that has the maximum impact on productivity, hence the material removal rate. This claim is supported by another study of Shah, and Patel

[44] where the impact of process parameters were investigated on granite material, in terms of the material removal rate. There was a mathematical model developed in order to predict the material removal rate with given process parameters. This model proved that feed rate has the highest impact on material removal rate, whereas pressure has a proportionate relation with it.

1.3.4 Parameter Effects on Various Materials

Palleda [45] did a study on the resulted taper angle and material removal rate at varying chemical domains such as phosphoric acid, polymer and acetone. In the cases where slurry was added to the environment, material removal rate resulted in being highest in the polymer. On the other hand, taper is not observed in the polymer environment. Among the acetone and phosphoric acid environments, taper hole is observed less in the phosphoric acid. As the concentration of the chemicals increase in acetone and phosphoric acid, material removal rate also enhances up to a threshold limit, then decreases. Kalirasu et al. [46] investigated the machinability performance of AWJ in polymer environment. In this study, the optimal values were found for stand-off distance, feed rate and pressure through applying multi objective optimization by ratio analysis to a function that involved both kerf taper angle and surface roughness. It was observed that feed rate had the most influence on both outputs. In addition to this, the optimum feed rate value worked better at lower thickness polymer material. It was seen that kerf taper angle and surface roughness had higher values as the thickness increased, therefore the mathematical model suggested in this study does not coincide with large thickness polymer material. Uthayakumar et al. [47] had a study on the machinability of nickel-based superalloys. In this study, the focus was on stand-off distance, feed rate and pressure parameters. It was found that at nickel-based superalloys feed rate and pressure affect the material removal rate the most. Pressure is the parameter that has the highest impact on surface quality and kerf wall inclination is mainly caused by pressure and feed rate.

CHAPTER 2

Parameter Selection Approach

AWJM has certain parameters that effect the entire process. Manual parameter selection can be accepted at times when there are not many constraints. However, the goal is to provide a general approach that can be applied to any sort of desired process. Parikh and Lam [4] divided these parameters into 4 categories such as hydraulic, mixing and acceleration, cutting and abrasive parameters. These categories consist of different parameters where; water pressure, water-orifice diameter and water flow rate are considered to be hydraulic parameters; focus diameter and focus length are mixing and acceleration parameters; traverse speed, number of passes, standoff distance and impact angle are cutting parameters; and lastly abrasive mass flow rate, particle diameter, particle size distribution particle shape and particle hardness are expressed as abrasive parameters. This study will focus on standoff distance, water pressure, traverse speed, and abrasive mass flow rate. It is crucially important to know how much a certain parameter affects the process and does not. Therefore, the approach was designed in a way that the parameters with highest affect will be given the most weight to.

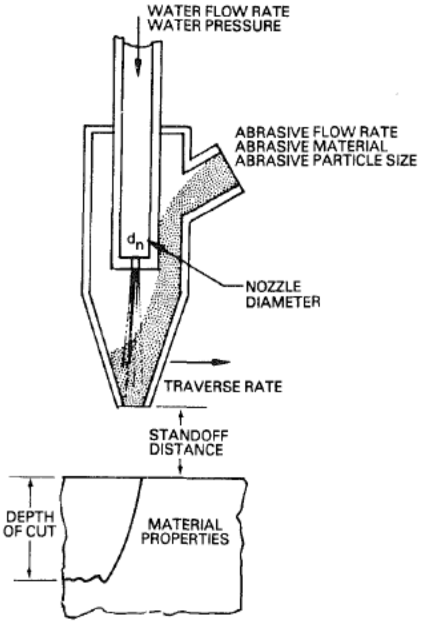

Figure 1: Abrasive jet nozzle [48]

2.1 Definitions

2.1.1 Water pressure

Per Hashish [34], the increase in pressure will result in an increase in cutting depth. High pressure will help with less usage of abrasive particles or allow traverse speed to be increased. This depends on the goal of the process, hence the objective function. Generally, the goal is to achieve overall minimum cost while the parameters are in a region of sufficient cutting performance. Hashish [34] has studied the effect of the water pressure on different parts of the process.

The water pressure effect on the depth of cut is proportional, meaning that as the pressure increases, a deeper depth of cut can be achieved. After the studies of Hashish [34], it was found that there is a critical value for pressure, as the threshold value. It was observed that when the abrasive flow rate was increased, the threshold for the water pressure was decreased.

It is safe to state that in most processes, it aims to cut the material as fast as possible. This will lead to increasing the cutting rates in order to achieve the minimum cycle time. Therefore, once water pressure is increased, cutting rates shall also be increased.

2.1.2 Water flow rate

Water flow rate has an important role in accelerating abrasive flow rate into increased velocities. However, increasing the water flow rate after a certain point may result in deceleration of the increase in depth of cut. That certain limit should not be exceeded since it may have some consequences. High water flow rates may demand larger nozzles for mixing, which may cause the energy of the particle impact to be less undiluted, hence a decrease in the overall energy of the abrasive particles. In addition to this, at high water flow rates the process may be environmentally hazardous [49].

2.1.3 Mixing tube diameter and mixing tube length

In order to enhance the performance of the process, mixing tube diameter can be decreased result in an increase in power density since mixing tube diameter is directly related to power density. This would allow smaller diameter mixing tubes to perform efficiently [49].

Mixing tube length has a direct relation with the material removal rate. The reason behing this is that mixing tube length has a significant impact on the jet's velocity. This relationship was shown by Blickwedel [50] in Figure 2, stating that as the tube diameter increases, material removal rate increases with it, even though the density of the particles decrease due to the increase on the tube length. This density decreases causes the velocity of the particles to reduce, hence the tube length impact the velocity of the jet.

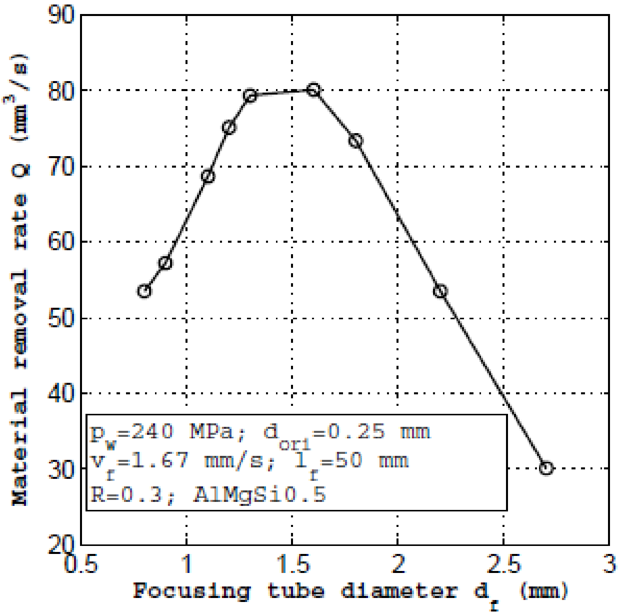

Figure 2: Focusing tube diameter vs. MRR [50]

At operations such as hole drilling, the tube length shall be increased since relatively short mixing tube lengths may result with a poor roundness effect. Similar to the roundness effect, mixing tube length also impacts depth of cut [34].

In addition to this Blickwedel [50] investigated the relationship between the tube length and the depth of cut in Figure 3. It is possible to interpret this relationship as, linear up to a certain threshold and then a slight decrease in the depth of cut.

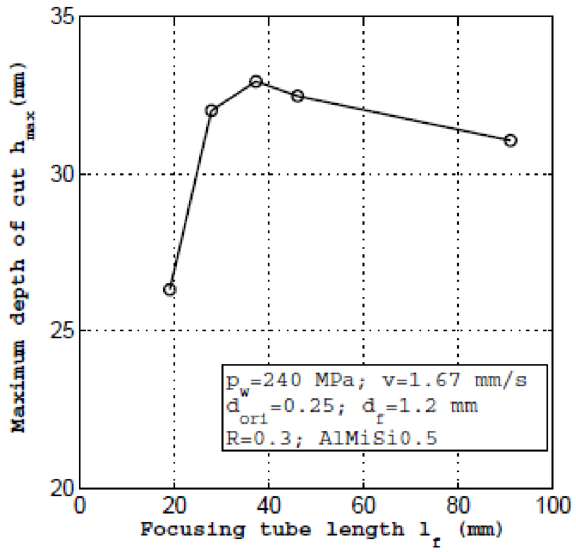

Figure 3: Focusing tube length vs. Max depth of cut [50]

2.1.4 Traverse speed

Traverse speed or feed rate in AWJM has a direct relationship with the depth of cut. Since the water is constantly running, the time spent on each part of the material is significant. Considering the study of Hasçalık et al. [51], as the traverse speed increases cutting depth decreases. Hence, the longer the jet stays at one spot, the deeper the cut will be. Therefore, traverse speed has a significantly important role in determining the intended depth of cut. It is important to maintain a constant speed throughout the operation both for a constant depth of cut and to avoid a rough edge resulting from the nature of the process. Its unit is millimetre per minute.

2.1.5 Number of Pass

Hashish [48] observed that as the number of passes increases the depth of cut increases as well. However, their study stresses the fact that the rate of increase is a more crucial issue to consider. It was found that with the number of the passes, this mentioned rate either decreases or stays constant after a certain point.

2.1.6 Stand-off Distance

The distance from the tip of the nozzle to the part surface is the stand-off distance. Generally, SOD takes values between 1-10 micrometres. It is an important parameter that highly affects the part's material removal rate, accuracy and depth of cut. In the studies of Madara et al. [52] it was found that, the increase in stand-off distance will cause a rougher surface, while decreased stand-off distance results in a better-quality surface finish. In the cases where the stand-off distance is high, the water jet will get the opportunity to extend before the cutting starts. Abrasive particles that exit the jet have a lower density, hence the jet's expanded flow. Therefore, the surface roughness will be higher. It should also be noted that Guo et al. [53] suggested that the optimal stand-off distance value shall be 2 mm.

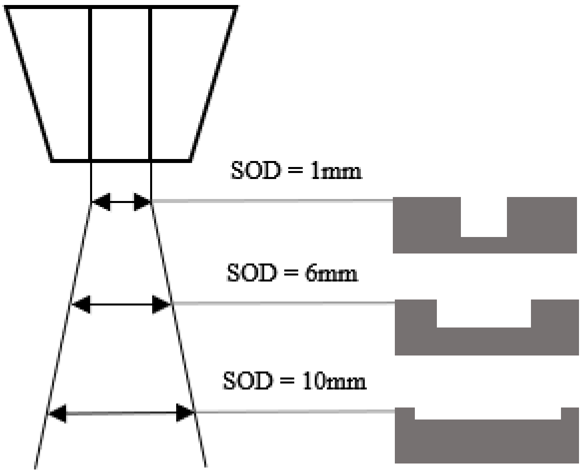

Figure 4: Effect of SOD on machined profile

2.1.7 Abrasive Mass Flow Rate

The amount of particles penetrating the stock material and the existing kinetic energy are determined by abrasive mass flow rate. This leads to the fact that high abrasive mass flow rates, have a foreseen increase in cutting performance. However, it should be noted that if the abrasive flow rate is too high, this may result in abrasive particles losing the kinetic energy they have. Therefore, the increase in abrasive mass flow rate should be followed closely.

It is also important to note that there is a threshold value for the increase in abrasive mass flow rate. Once this value is surpassed, the depth of cut tends to decrease, as shown through Figure 5, even though the abrasive mass flow rate has a proportional relationship with the depth of cut.

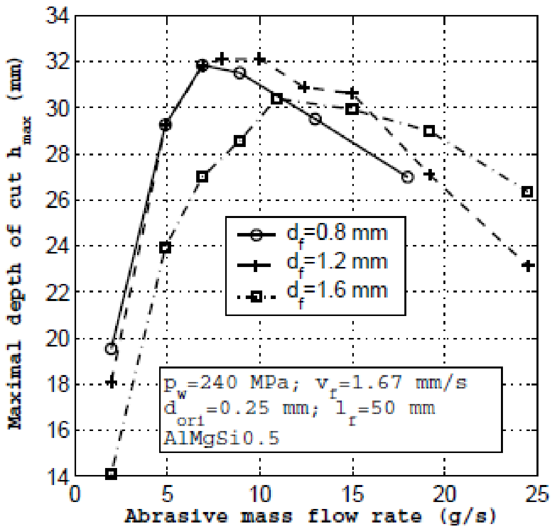

Figure 5: Abrasive flow rate vs. Max depth of cut [54]

2.1.8 Particle part diameter, size distribution, shape, hardness

Different sizes of abrasive parameters are suitable for different materials. Medium size can be classified as mesh 60 which is used for steel. Thinner size particles would be mesh 100 and 150, whereas grander particles would be mesh 36 and 16 [34].

According to Hashish [34], grander abrasive particles tend to have a higher roundness value. It is important to note that while comparing the same abrasive flow rate at two abrasive particles with different sizes but having everything else the same, the smaller abrasive particles would have a higher chance of cutting successfully compared to grander particles. Although, small particles may have their kinetic energy level decreased due to their size.

Figure 6 shows that particle size significantly affects on the depth of cut, where larger particles result in higher depth of cut. Pi [55] concluded that rather smaller particles do not result in being as sensitive as the larger particles to the change in abrasive mass flow rate.

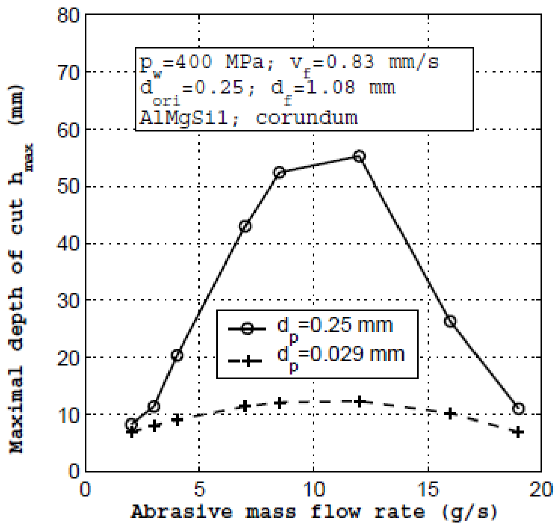

Figure 6: Abrasive particle diameter vs. Max depth of cut [54]

2.2 Parameter Selection Approach

In order to investigate the relation between the parameters, the design of experiment was done. Forty-eight tests were conducted by giving specific ranges for four main parameters: abrasive flow rate, water pressure, stand-off distance and traverse speed (feed rate).

Table 1: DoE values for parameters

Parameter	**Unit**	**Values**
Water pressure	Mpa	100, 200, 250, 350
Feed	mm/min	500, 1000, 2000, 3000, 6000
Abrasive rate	g/s	2, 4, 5, 7
Stand-off distance	mm	2, 4, 6

In the design of experiments, parameters were matched with one another in order to obtain coherent results. While the inputs were the parameters as mentioned earlier, the output was the kerf depth, stated as the depth of cut. Once the test matrix was completed and the toolpath was generated, 3 channels tested each condition. To obtain the kerf depth values, each channel was measured by a surface gauge from different points of depth, in order to have the most accurate result.

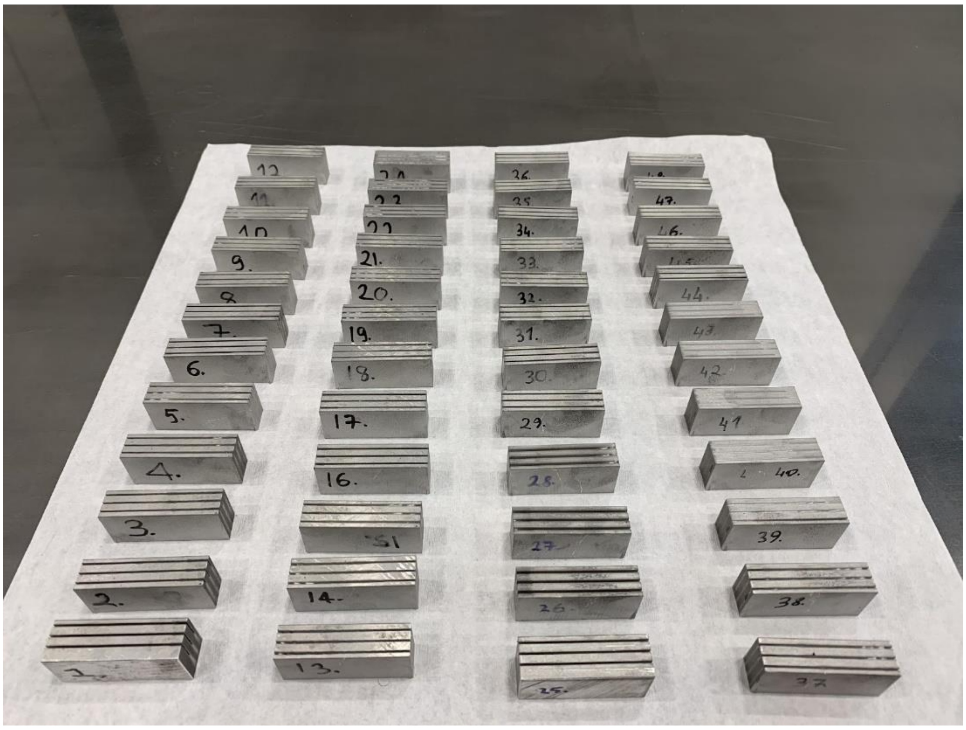

Figure 7:Parts machined for the DoE

2.2.1 Objective Function

It is essential to state the objective function in order to emphasize the goal of the approach. The goal with this approach is to minimize the overall cost that is spent in order to machine a desired part and to machine the desired part at an optimal and minimum time. In this case, there will be two objective functions minimizing the cost and finding the minimum cycle time.

First off, the objective function for cycle time is stated. Cycle time is dependent on the total length of the part, depth of cut, feed rate and the function that is dependent on feed rate, pressure, and abrasive flow rate. The relation among the main parameters are shown below as the function of r (1).

$$r = f(V_{feed}, \dot{m}_a, P) \tag{1}$$

Total length is stated with L, which can be adjusted according to the perimeter of the geometry. The depth of cut at each step is stated as d. Since the depth of cut is affected by the function of r, d shall be divided by r. Once the length and the parameters relation are computed, the value divided by the feed rate will give the cycle time.

$$t = \frac{L * \frac{d}{r}}{V_{feed}} \quad (2)$$

Cost function requires its own objective function since there are fixed and variable costs, and the values that parameter the cost and cycle time functions may be different. The costs that shall be considered for the cost function are machine tool, labour, orifice, nozzle, water, and abrasive cost. The fixed costs can be stated as the machine tool cost and labour cost, whereas the variable costs are the orifice cost, nozzle cost, water, and abrasive cost. It should be noted that machine tool cost includes the maintenance and energy consumption costs. The total cost can be computed by adding up all unit costs and multiplying with the time spent on that operation.

$$c = (C_m + C_l + C_o + C_n + C_w + C_a) * t \quad (3)$$

In the equation above, C_m stands for machine tool cost, C_l for labour cost, C_o for orifice cost, C_n for nozzle cost, C_w for water cost and C_a for abrasive grain cost. The cost for each variable is given below.

Table 2: Variable costs per unit time [56]

Variable	**Cost**	**Unit**
Machine Tool Cost	0.11	$/min
Labour Cost	0.15	$/min
Orifice Cost	0.01	$/min
Nozzle Cost	0.03	$/min
Water Cost	0.009	$/min
Abrasive Cost	0.0002	$/gram

2.2.2 Parameter effects

As it was previously mentioned, the main four parameters are considered to be the feed rate, stand-off distance, abrasive flow rate and pressure. In order to see the interrelation of these parameters, multivariate regression was performed by keeping the stand-off distance value constant. Thus, it is possible to observe the change among the parameters with respect to one another.

In Figure 8, it can be seen that there is a linear relationship between the feed rate and pressure, for the values starting from 1000 mm/min and onwards for feed rate. Figure 8 results from the observations at different abrasive flow rates where the stand-off distance value is 2 mm.

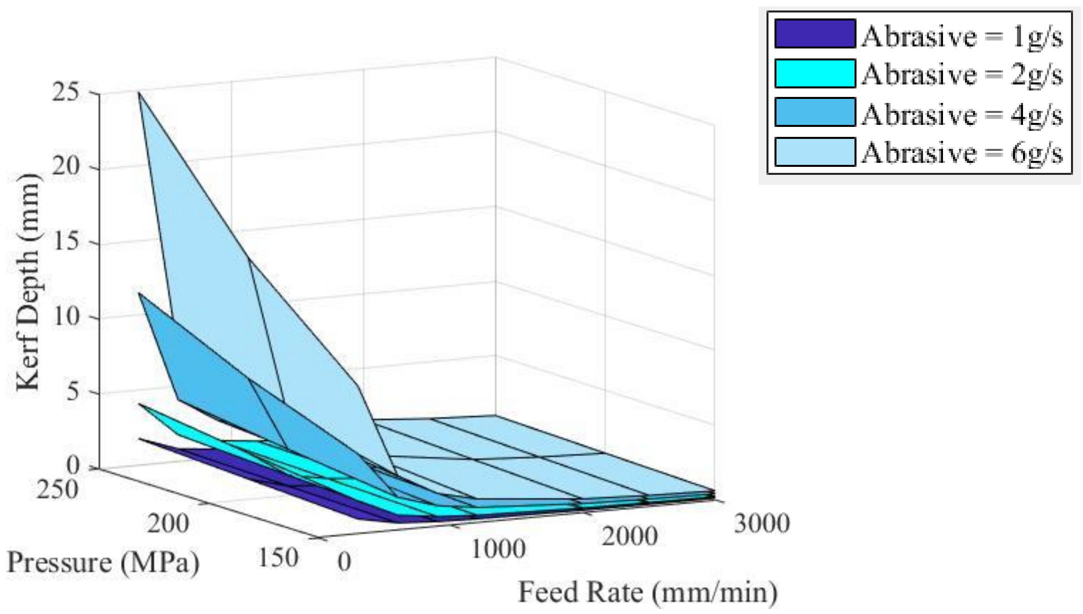

Figure 8: Feed rate vs. Pressure at different abrasive flow rate levels

Figure 9 shows the relationship between the feed rate and abrasive flow rate at different pressure values. It is possible to say that there is a similar relationship to feed rate and pressure observations. There is linearity between the stated parameters for the values 1000 mm/min and onwards of feed rate.

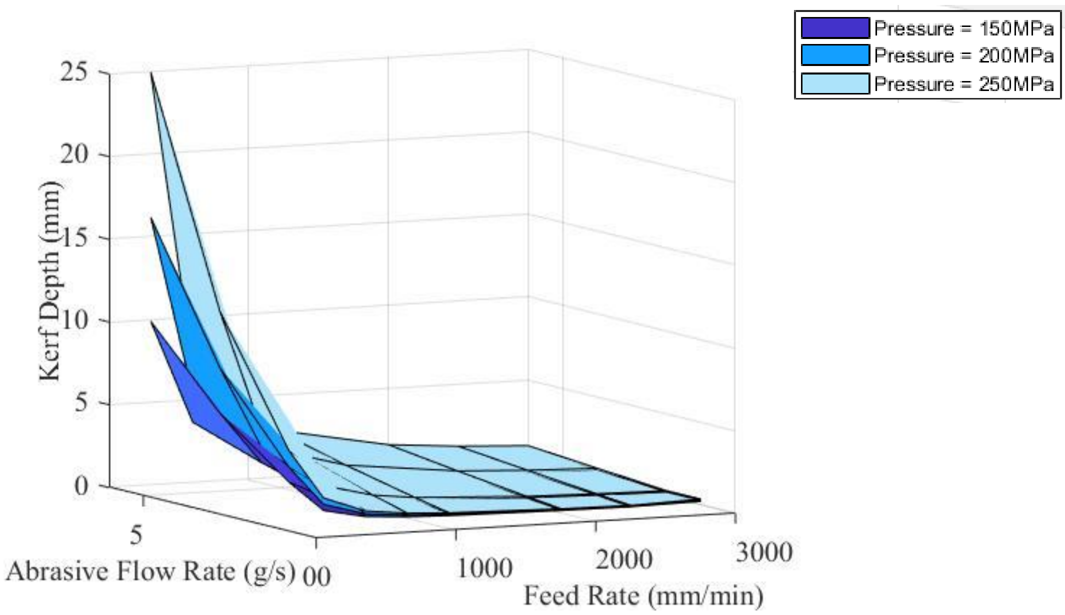

Figure 9: Feed rate vs. Abrasive flow rate at different pressure levels

In Figure 10, it is possible to see the relationship between pressure and abrasive flow rate at different feed rate values. Low feed rate values result with high kerf depths, whereas pressure and abrasive flow rate have a linear relationship among each other.

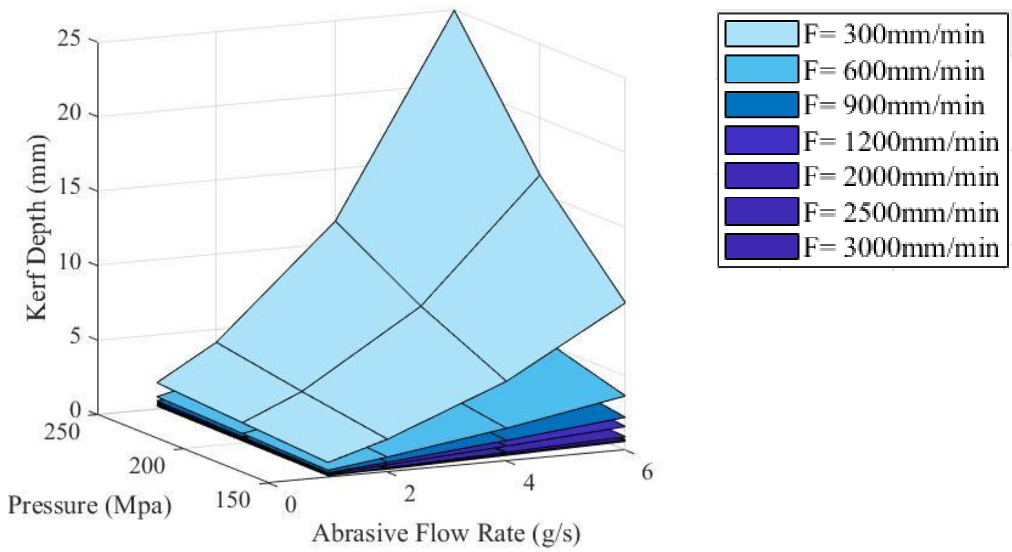

Figure 10: Abrasive flow rate vs. Pressure at different feed rate levels

Considering the relationships among the main parameters, a multivariate regression was performed in order to obtain an equation where it is possible to see the contribution of each parameter in the output of kerf depth. The equation below indicates the mathematical relation given by the function r, where the effects of parameters were shown in one function. In addition, it gives a numeric value for the kerf depth.

$$r = 0.0117621 * P + 0.0706794 * \dot{m}_a - 0.0009593 * V_{feed} + 2.186013 \quad (1)$$

As it can be seen from the equation, the parameter that has the most dominant effect on kerf depth is abrasive flow rate, followed by water pressure. The feed rate has a negative coefficient, indicating that higher a feed rate yields to a lower kerf depth.

2.2.2.1 Effect of Stand-off Distance

As it can be seen in Figure 11 the difference in sod does not have a significant effect on different kerf depths. SOD values that are close to each other approximately result in the same kerf depth. Therefore, it is possible to say that, since the SOD values are close to each other, there isn't a significant difference in kerf depths. Even though the figure below does not show, it is also important to note that stand-off distance has a more significant impact on kerf width. Kerf width tends to enlarge as the stand-off distance value gets higher.

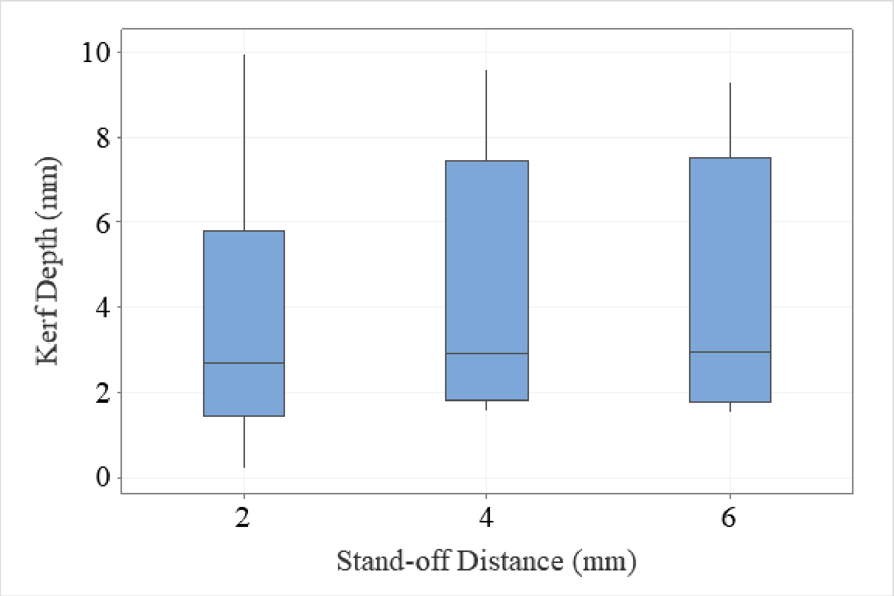

Figure 11: SOD vs. Kerf depth

Observing the collected data and Figure 12, shows that each value for stand-off distance shows a similar result for each feed rate, which means that, feed rate change affects every stand-off distance value similarly. Therefore, it is safe to say that there is no significant relation between stand-off distance and feed rate since the change in feed rate does not change the behaviour of stand-off distance. In addition to Figure 12, Barton [57] also studied a linear relationship between the increasing feed rate and decreasing stand-off distance.

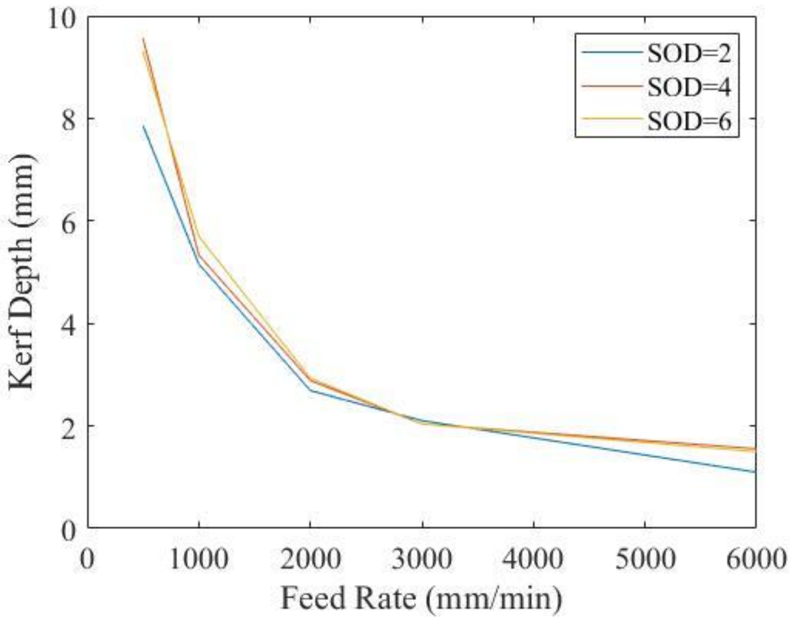

Figure 12: Feed rate effect on kerf depth at constant abrasive rate and pressure

According to the study of Mohammad et al. [58], where experiments were performed at a high range of stand-off distances, it was concluded that at higher stand-off distances, the abrasive particles acquire higher kinetic energy. However, due to wide kerf widths, the abrasive particles descending kinetic energy. Therefore, at higher stand-off distances, abrasive particles fall into a decline.

The relation between the stand-off distance and pressure was not found to be significant. Furthermore, after doing the experiments in the DoE, it was seen that the result did not make a significant difference among different SOD values at different pressures. Therefore, it can be said that there is not a remarkable relation among the parameters stand-off distance and pressure.

2.2.2.2 Effect of Abrasive Flow Rate

It is possible to say that an increased abrasive flow rate will lead to increased kerf depth. However, there is a certain threshold for the abrasive rate value. As Hashish [49] mentioned, threshold value determines the maximum value for the abrasive flow rate to result in an increased kerf depth.

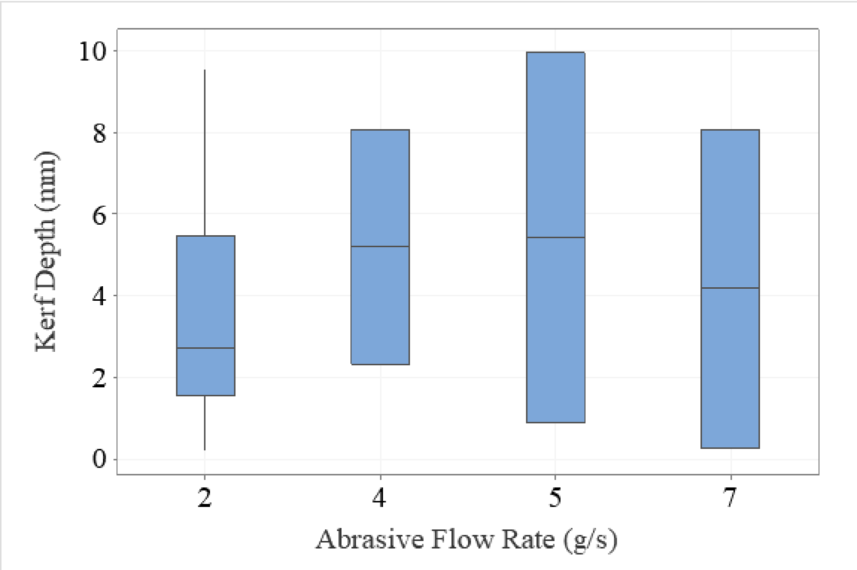

Figure 13: Abrasive flow rate effect on kerf depth

When the abrasive flow rate is observed at different feed rates, it can be seen that at a constant stand-off distance and water pressure, higher feed rate results with lower kerf depth as the abrasive flow rate increases. In contrast, at lower feed rate, kerf depth increases with the increasing abrasive flow rate. This can be concluded as, at higher feed rates abrasive flow rate does not make a significant difference in terms of kerf depth; however at lower feed rates, the cut also becomes deeper by increasing the abrasive rate.

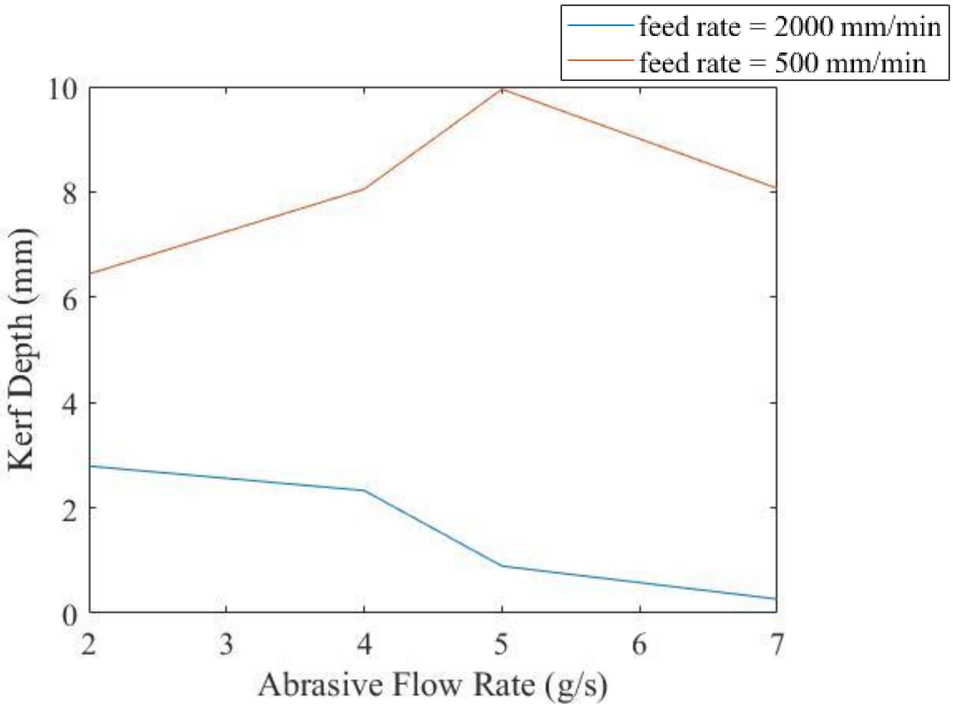

Figure 14: Abrasive flow rate at different feed rates

Pressure and abrasive flow rate have a moderate relationship where the depth of cut increases with an increase in both pressure and abrasive flow rate. However, it is also safe to say that the particular parameters affect the result of depth of cut likewise, meaning that increased pressure or abrasive flow rate leads to an increased depth of cut. Therefore, even though a direct relationship cannot be determined, it is possible to say that particular parameters do affect the result. Hence, it is concluded that the parameters abrasive flow rate and pressure have a moderate relationship.

In addition to this, abrasive flow rate significant affects surface quality and width of cut [49]. As the abrasive rate increases, the width of the cut – in addition to the depth of cut – also increases. Therefore, surface quality tends to get better with increasing abrasive flow rate due to a decreasing height of burr, all considering this is the case until a threshold value for abrasive flow rate.

2.2.2.3 Effect of Feed Rate

The feed rate and pressure relationship was determined by observing the depth of cut results at different feed rate and pressure values while keeping the abrasive flow rate and stand-off distance values constant. As shown in the figure below, higher pressure leads to an increased depth of cut when the feed rate is lower. Therefore, it can be said that there is a significant relationship among the particular parameters where feed rate is increased, the pressure shall be decreased in order to achieve the intended depth of cut. Hence, the relationship level is significant.

In general, feed rate has an inverse proportional effect on the depth of cut. Hence as the feed rate increases, the depth of cut results tends to get lower. As it can be seen from Figure 15 where the results were obtained through the DoE, every value for feed rate has its own range. Therefore, it is important to pay attention to the rest of the parameters while selecting a feed rate, since deciding on this particular parameter alone may have misleading results considering the fact that some feed rate values have higher ranges.

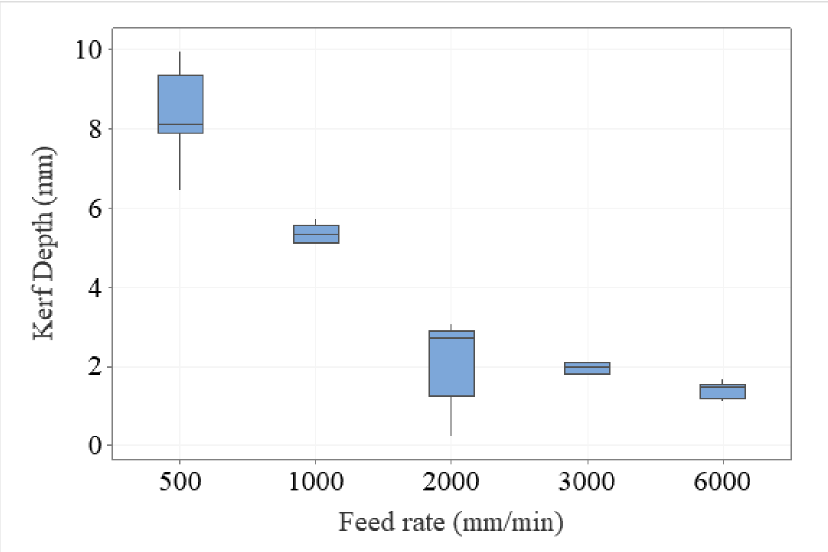

Figure 15: Feed rate effect on kerf depth

2.2.2.4 Effect of Pressure

Depth of cut effect can be observed from the collected data. At low pressure values, there is a lower range in depth of cut. As the pressure increases, it is possible to achieve wider range of depth of cuts.

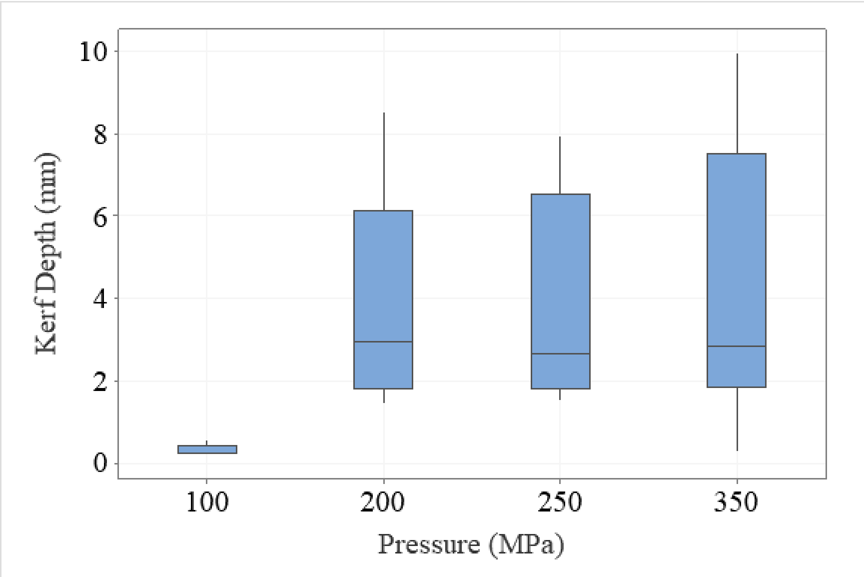

Figure 16: Pressure effect on kerf depth

Pressure has a significant effect on surface quality, where the pressure has increased the waviness of the surface decreases [49]. To generalise, it is possible to say that high pressure leads to better surface quality. Although, it should be noted that at high pressure values abrasive flow rate and the feed rate may not be stable. At this occurrence, more attention should be paid to abrasive flow rate and feed rate values.

As previously mentioned, low pressure results in a lower depth of cut in comparison to higher pressure values. Considering the fact that different pressure levels result differently, it is safe to say that there is a significant relationship between the pressure and feed rate.

2.2.3 Constraints

Each parameter has its constraints. In order to have the intended kerf depth without having the surface quality or kerf width issues, it is important to decide on the values within the scope of their constraints.

2.2.3.1 Abrasive Flow Rate

Even though the abrasive flow rate can reach its maximum capacity at the water jet robot in theory, it cannot be utilized from the water jet's capacity. From the previous experiments, it was seen that abrasive flow rate at 10 g/s resulted with clogged channels. Therefore, the intended kerf depth was not achieved at all. Hence, keeping the abrasive rate under a certain value is safe to avoid the clogging issue.

Another constraint for abrasive flow rate would be the effect on surface quality. At a high abrasive flow rate, surface quality is expected to worsen since abrasive particles come into collision at high rates and have their kinetic energy diminished. This would result in poor surface quality [59].

2.2.3.2 Stand-off Distance

Stand-off distance has a direct relation with the kerf shape and an important role in uniformity. Therefore, in order to have a good surface quality, it is important to select a lower stand-off distance since high SOD is directly related to surface roughness. Furthermore, Selvan et al. [59] showed in the study that once the stand-off distance increases, the kinetic energy at the impingement decreases. Thus, surface quality gets worse. Therefore, for stand-off distance, the biggest constraint is the surface quality, so it should be kept as low as possible.

2.2.3.3 Feed Rate

High feed rate leads to a shorter cycle time. However, this may result in poor surface quality as a consequence of a smaller number of abrasive particles will get the chance to penetrate at a shorter time. Thus, the feed rate cannot be increased to an unrestrained rate since its constrained by the surface quality.

2.2.3.4 Water Pressure

High pressure leads to better surface quality. Although, it should be noted that if high pressure is used in an operation, feed rate and abrasive flow rate will be more sensitive to a certain change in value, as previously mentioned [49]. Therefore, high pressure should be the goal to achieve while keeping the feed rate and abrasive flow rate parameters considered. Water pressure's constraint is the feed rate and abrasive flow rate.

All in all, the constraints can be summarized under the surface quality and clogging issue that is caused only by high abrasive flow rate. Every parameter has a constraint in terms of surface quality as aforementioned. Therefore, it is important to keep these constraints in mind while making decision on parameter values.

2.2.4 Parameter Interrelation

Table 3: Parameter interrelation

Parameters	Feed	Pressure	Abrasive	SOD
Feed		2	3	1
Pressure	2		3	1
Abrasive	3	3		2
SOD	1	1	2	

3:highest interrelated - 2:medium interrelated - 1:least interrelated

Observing Table *3*, it is possible to say that the most interrelated parameters are pressure and abrasive flow rate. Feed rate has a medium relation with abrasive flow rate and pressure. Stand-off distance, however, has the least interrelated relation with feed rate and pressure. There was also the best subset regression done on the observed values, taking kerf depth into account. From this regression, it is possible to see that abrasive flow rate and pressure are the two parameters that affect the kerf depth; hence the material removal rate the most.

2.2.5 Approach

For a general view of the approach, it is important to make the decisions according to the order that is given in the chart below.

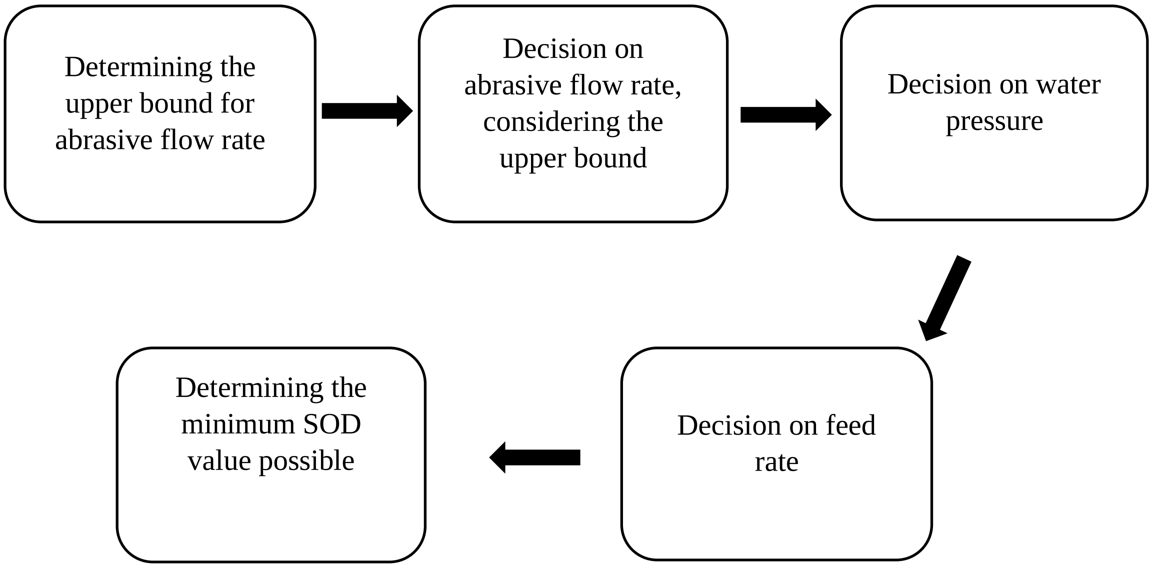

Figure 17: Flow chart of the approach

As mentioned in previous sections, every parameter has a different interrelation with one another. Therefore, even though there are 4 main parameters to consider, it is possible to give selection priority to the ones that have the most interrelation. In addition, all parameters have somewhat significant constraints. It was seen that the most common constraint is the surface quality issue. Bearing the constraints in mind, an approach is suggested as ordered parameter selection.

As it can be seen from Table *3*, parameters with the highest interrelation are pressure and abrasive flow rate. Considering the output, hence the intended kerf depth, a value should be selected for these parameters. In terms of minimum cycle time, high feed rate and high-pressure values may seem as a favorable choice, however, the process does not result in the best quality surface finish. Therefore, deciding on pressure first and then deciding on feed rate while considering the fact that at high pressure values, it should be noted that high feed rate may be critical or not result in the intended surface quality or kerf depth.

For determining abrasive flow rate, it is important to know the maximum capacity of the water jet robot. Having the abrasive flow rate at 100% capacity will most likely result in clogging. However, it was observed in this study that even at 75-80% capacity clogging may be an issue. Therefore, it is important to take this into account and choose an abrasive rate that will not result in clogging, together with other parameters.

Since feed rate, pressure and abrasive flow rate are now determined, choosing a correct stand-off distance is important. As mentioned in previous sections, stand-off distance shall be chosen as minimum as possible. As a rule of thumb in this study, the minimum value was selected as 2 mm. In other cases, this number may vary, but the end goal is to work with the smallest stand-off distance possible.

To sum up this approach, first pressure and abrasive flow rate shall be decided on. Once these are set, the feed rate must be defined. Finally, after having all 3 parameters, stand-off distance shall be chosen.

2.3 Summary

In this chapter, the relation among four main parameters, their effect on kerf depth and constraints of each parameter were stated. By keeping the stand-off distance constant, multivariate regression was done in order to see the numerical relation among abrasive feed rate, pressure, and feed rate. It was seen that abrasive feed rate had the highest impact on determining the kerf depth, followed by pressure and feed rate values. This formula was used to compute the cycle time of a given process, and compute the total cost of the process, using the computed cycle time. The cost of each variable is given. After seeing all the relations, the interrelation was shown, and an approach was suggested. Since abrasive flow rate has the highest influence on kerf depth, it is suggested to choose it first. This is followed by determining the pressure and feed rate values. As the last step, the stand-off value shall be chosen as the smallest value possible. While determining the values, maximum levels of the parameters must be taken into account, considering the constraints for each parameter.

CHAPTER 3

Minimization of Time and Cost

Two types of algorithms were used in order to compute the minimum cycle time and cost. The explanations of gradient based, and gradient free algorithms are given in this section. For both of these algorithms, total cycle time and total cost are minimized for an AWJM operation. Explanations are given in each section, in addition to mentioning the effects and results of each parameter. Finally, both algorithms are compared at the end of this chapter in terms of the overall cost and time minimization results.

3.1 Gradient Based Algorithm

Optimization algorithms can be classified into two main groups such as gradient based and gradient free algorithms. While focusing on gradient based algorithms in this section, it is important to note that this type of algorithm is based on derivatives. Gradient based algorithm steps can be explained as such:

1. Searching direction works by taking the derivative of the slope at its present location. The slope is applicable at one dimension. In this case, where there are more than one dimension, this is the gradient. Once the gradient is computed, then the search direction is determined.
2. Step size is determined by the solver. Once the step size is chosen, the previously determined direction is followed by the solver with its step size. After this movement, the solver checks if the minimum is reached. This may not be the case

where the goal is reached. In order to compensate for this, a new direction and step size are chosen.

3. Convergence check denotes the minimum of the function. Previous steps are repeated until the minimum; hence the convergence is reached.

In this case, the FMINCON solver is used. This solver is helpful in cases where a non-linear objective function and constraints are present, and the objective function is desired to be minimized where there are multi variables. FMINCON is useful in cases where it is necessary to find the minimum of a constrained function. It should be noted that, this solver starts its search by an initial solution, which is given by the user. If there are any, linear inequalities should also be defined. It is a must to define upper and lower bounds for each variable, hence the range is defined for variables. The inputs and outputs can be summarised as such:

Inputs

- The objective function
- Initial solution
- Linear inequalities and/or equalities
- Upper and lower bounds
- Nonlinear inequalities and/or equalities

Outputs

- The minimized solution for the objective function
- The exit condition of the solver
- Structure of the output
- Lagrange multipliers of the solution
- Gradient of the solution

3.2 Genetic Algorithm

Genetic Algorithm (GA) is biology inspired optimization technique that holds crossover, selection and mutation operant. It is a gradient-free algorithm, meaning that the first or second derivatives are not computed during the computation process. This is an algorithm that resides in the class of evolutionary algorithm and it operates with a population by using the natural genetics and selection optimal solutions are derived [60]. One of the significant differences from conventional algorithms is that GA works with the population of optimal solutions. GA steps are as follows:

1. A random population is generated initially.
2. In order to compute the fitness value, every one of the solutions is criticised.
3. The goodness level of the solution is decided on by taking the fitness value into consideration. The higher the fitness value, better solution is acquired.

Population operators such as reproduction, crossover and mutation have the duty to originate a new population in order to determine, test and decide on the sufficiency of the termination criterion.

4. The reproduction operant is responsible for structuring a mating pool by determining the reasonable solutions from the population that is at present. While doing this, it takes the fitness value into account.
5. Crossover operant takes the crossover probability into account in order to originate better and even new solutions taken from the mating pool, by crossing over them.
6. Mutation operant must work in order to establish a locally decent/better than the previous solution and sustain the dissimilarity in the population.
7. These are on-going steps until either the criteria for termination is met or the number of stated generations is reached.

It is possible to classify GA in two categories such as real-coded and binary. In binary, the optimal solution relies on the string length of the decision variables. Real-coded however, uses different parameters [3]:

- Reproduction operant uses tournament selection,
- Crossover operant uses simulated binary crossover (SBX),
- Size of the population,
- Number of generations,
- Probability of the crossover,
- Probability of the mutation,
- SBX parameter,
- Polynomial mutation parameter.

Bagchi [61] mentioned that the parameters that have the most influence in real-coded GA are the size of the population, polynomial mutation parameter and SBX parameter. It should be also noted that the population size shall be multiplied by the number of decision variables. Run time is the determiner of the number of amounts the optimization problem will be solved where it is possible to solve the problem for different parameter combinations.

3.3 Minimized Cycle Time Computation by FMINCON Solver

Cycle time is the main output to be minimized as the objective function. Both gradient based and gradient-free based algorithms were applied in order to compare the results. For both cases, a desired minimum thickness that can be achieved is set as 4 mm, meaning that during an AWJM operation the minimum kerf depth that can be removed is set as 4 mm. The length of part is set as 100 mm. First, the gradient based algorithm was applied, hence the FMINCON solver. This is considered to be a multi-level cut, meaning that the time will give the total cycle time, whereas the r value will indicate the amount of material removed at each pass. It should be noted that r is the function that shows the relation among the parameters and gives parameter values in order to minimize the cycle time, which also results in the value of depth of cut at each pass. Desired thickness is indicated as the *thickness* of the workpiece.

The inputs that shall be computed by the algorithm are the pressure, feed rate and abrasive flow rate values. The outputs that are asked for this case are the cycle time, the parameters of abrasive flow rate, feed rate and pressure, the solver's exit condition, and the structure of the output. An initial solution is necessary for this algorithm, therefore the lower bound of the parameters were considered as the initial solution. There are not any linear/non-linear equalities/inequalities for this case. However, upper and lower bounds have crucial importance. Parameter ranges are given below.

$$100\ MPa \ll pressure \ll 350\ MPa \tag{4}$$

$$1\ g/s \ll abrasiveflow\ rate \ll 6\ g/s \tag{5}$$

$$500\ mm/min \ll feed\ rate \ll 4000\ mm/min \tag{6}$$

The thickness of the workpiece, hence the intended depth was ranged between 4 – 20 mm, however it is possible to increase the upper range, if a higher thickness part is intended to be machined. It was observed that in order to minimize the cycle time, the solver results in the pressure at its highest value. However, the abrasive flow rate tends to result at its lower range. Feed rate depends on the depth of cut since high feed rate leads to a lower depth of cut. Therefore, it was expected to observe an inverse proportion among r and feed rate values. It was seen that feed rate was the parameter that varied the most. Considering that feed rate is directly related to productivity, it is not unexpected to claim that cycle time minimization is mainly related to feed rate values. It is also possible to observe that time increases with the depth of cut, which is expected.

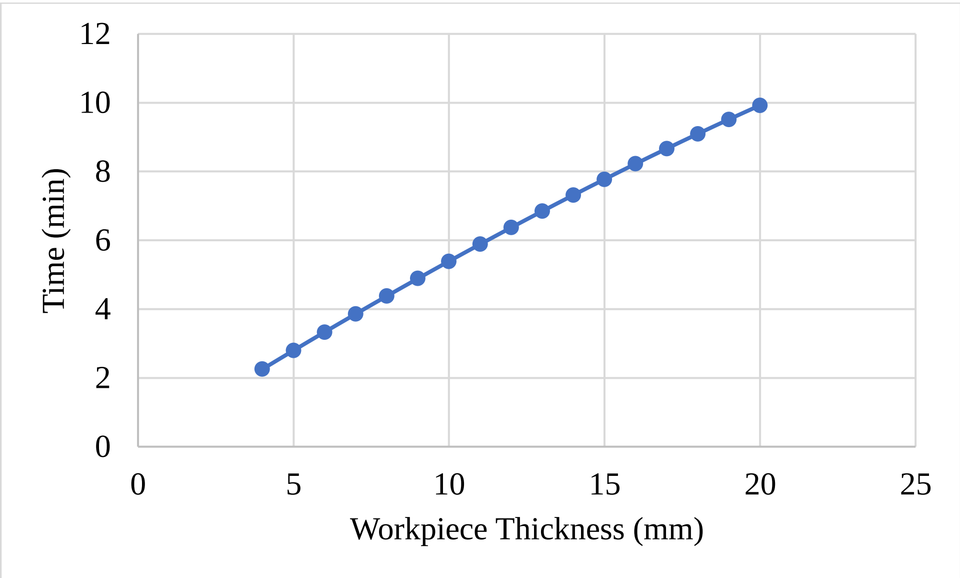

Figure 18: Workpiece thickness vs. Time for FMINCON

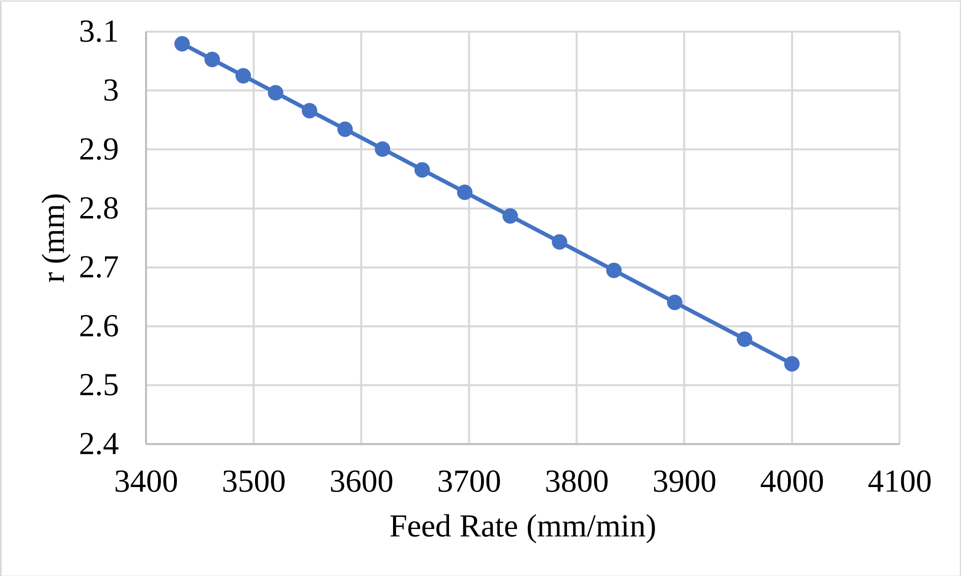

Figure 19: Feed rate vs. r

3.4 Minimized Total Cost Computation by FMINCON Solver

In addition to time, there is also a cost function in order to minimize the cost of an operation. In this case, the objective function is minimized cost. Therefore, the parameters were selected accordingly by the solver. In this case, the output parameters will be the same except that instead of obtaining minimized time, minimized cost is acquired. However, inputs differ from cycle time minimization significantly. Firstly, the cycle time has to be computed in order to find the cost per minute for the operation. Time is computed as in equation (2), which is then multiplied by the summation of unit costs. Machine tool cost, labour cost, orifice cost, nozzle cost, water cost and abrasive cost are the inputs. Therefore, the output will reflect the result of equation (3). In this case, the solver resulted in both maximized pressure and abrasive flow rate values. Since cycle time is involved in this objective function, the determining parameter is once more feed rate. As it can be observed from Figure *20*, feed rate has an inverse proportionate relation with total cost. This is due to the fact that, productivity increases with feed rate. Therefore, the observation is expected. Total cost also increases as the r value increases. As the amount of material removed increases, it is inevitable to observe an ascending result in total cost as it can be seen from Figure 21.

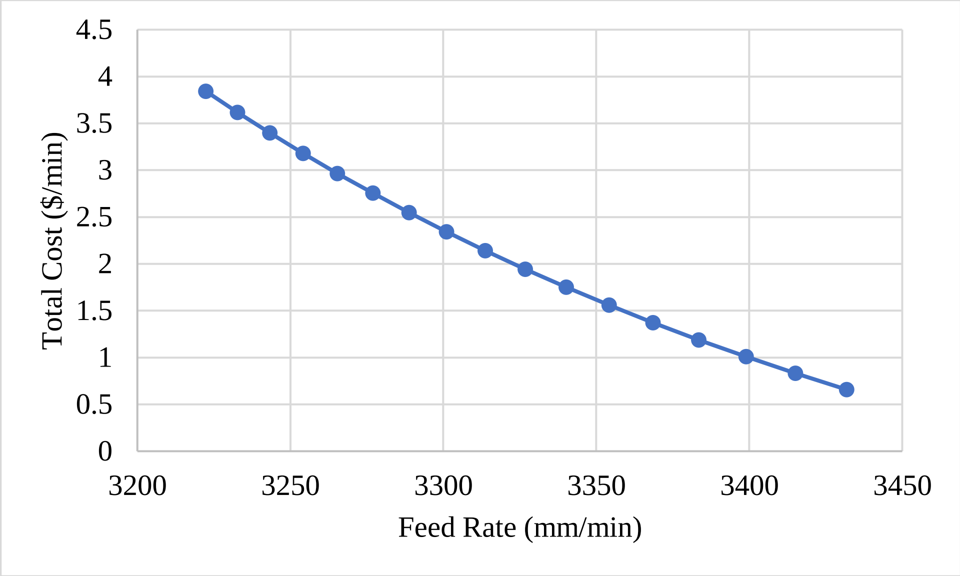

Figure 20: Feed rate vs. Total cost

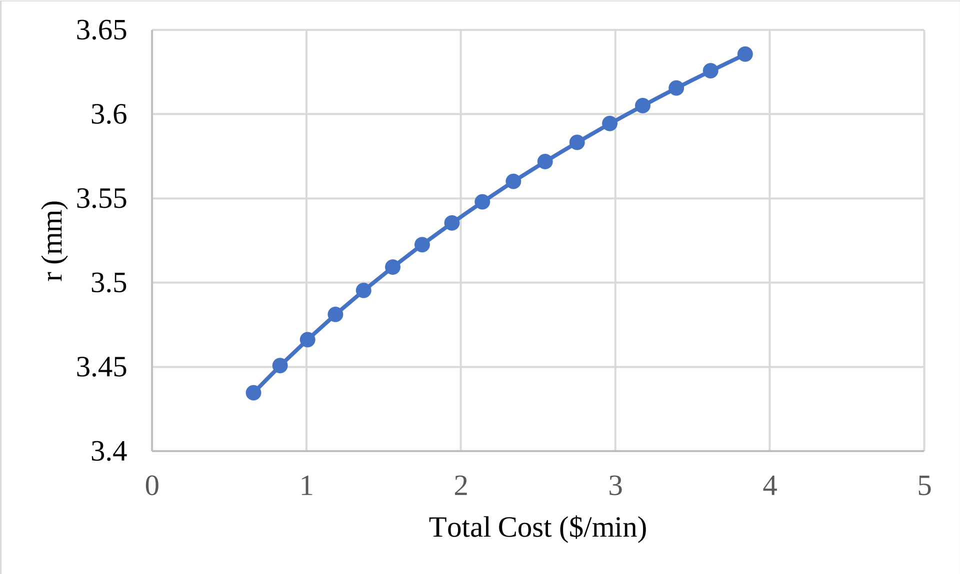

Figure 21: Total cost vs. r

3.5 Minimized Cycle Time Computation by GA

The objective function of this algorithm is the same as the function used at FMINCON solver. One of the major differences is that there is not an initial solution that is indicated. This algorithm is a probabilistic stochastic search algorithm; therefore, it is based on randomness. Hence, each run of the solver results differently. Thus, the results that fit the stated problem the best were chosen. The number of variables must be stated as an input to the function, which is 3 in the current case. These three variables are abrasive flow rate, pressure, and feed rate parameters. In addition to this, lower and upper bounds should be given as inputs. This algorithm tended to choose the maximum pressure and minimum abrasive flow rate values in order to minimize the total cycle time. Feed rate was the parameter to determine the cycle time, hence the material removed at each level. It is seen from Figure 22 that total cycle time increases with the thickness of the workpiece.

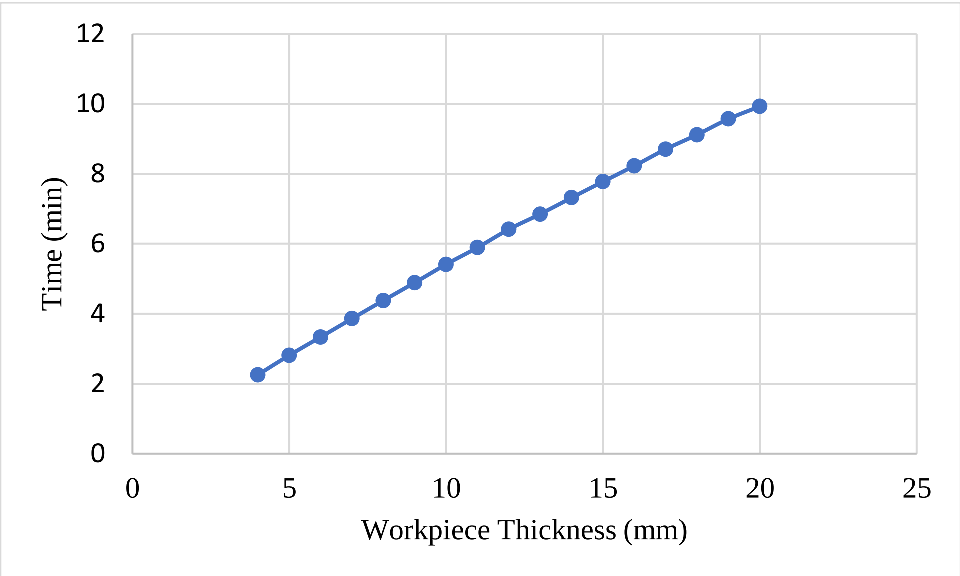

Figure 22: Workpiece thickness vs. Time for GA

3.6 Minimized Total Cost Computation by GA

As previously mentioned, cost computation is significantly different from cycle time computation due to its objective function. In this case, the objective function is to minimize the total cost while determining the parameter values favouring the minimized total cost. The case for GA is not different than FMINCON solver. As the thickness of the workpiece increases, total cost also increases which can be seen in Figure 23.

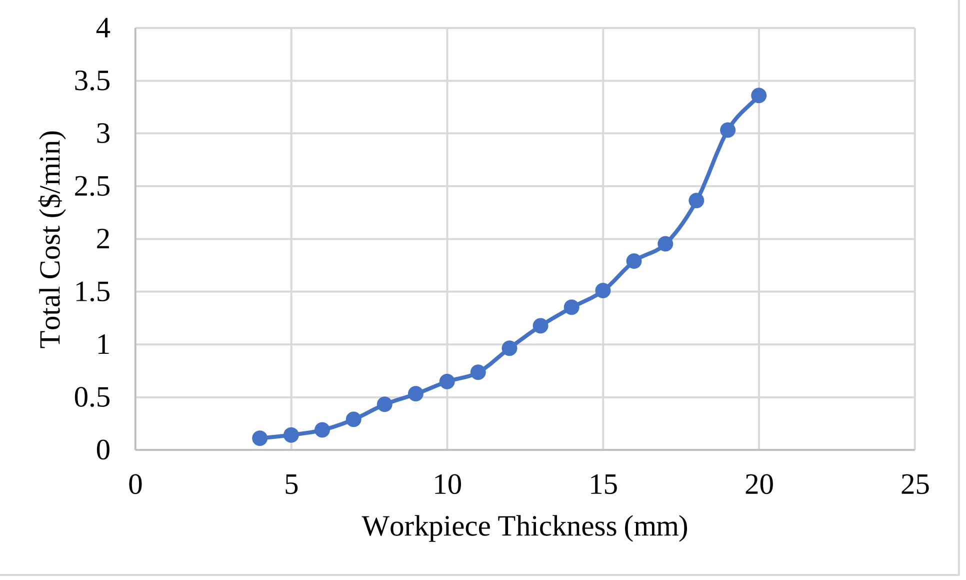

Figure 23: Workpiece thickness vs. Total cost for GA

As expected, pressure and abrasive flow rate values are chosen at the upper range. Whereas feed rate is the determiner of the productivity of the operation, hence its variation in comparison to other parameters.

3.7 Comparison

After minimizing time and cost at both gradient based and gradient free algorithms, it was seen that the overall calculations are not significantly different from one another. The pressure resulted as being at its upper range for all computations whereas abrasive flow rate was at its minimum for time computation and maximum for cost computation at both algorithms. It was seen that feed rate is the determining parameter, considering the fact that feed rate is responsible of the productivity, this was an expected result.

As it can be observed from Figure 24, both algorithms overlap at their result for minimized time. Meaning that, both algorithms are reliable in terms of computing the minimum cycle time for an operation at AWJM.

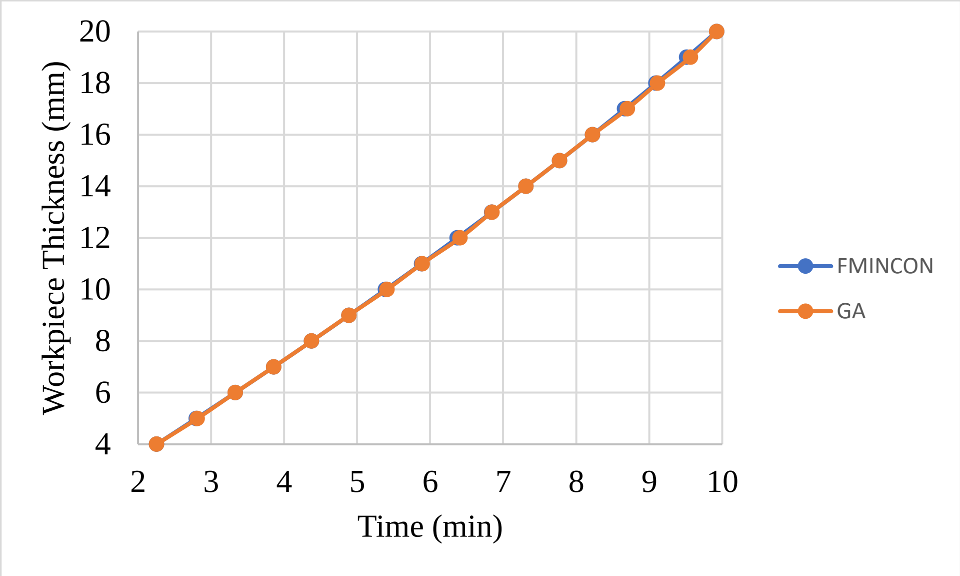

Figure 24: FMINCON & GA vs. Time

In terms of cost, it is possible to see that FMINCON solver had a linear result, where GA was not computed to be as linear as FMINCON due to its random nature, from Figure 25. However, the overall result does not differ significantly. Cost increases in both cases as the thickness of the workpiece gets larger. Therefore, it is possible to say that both algorithms resulted consistently in cost computation as well.

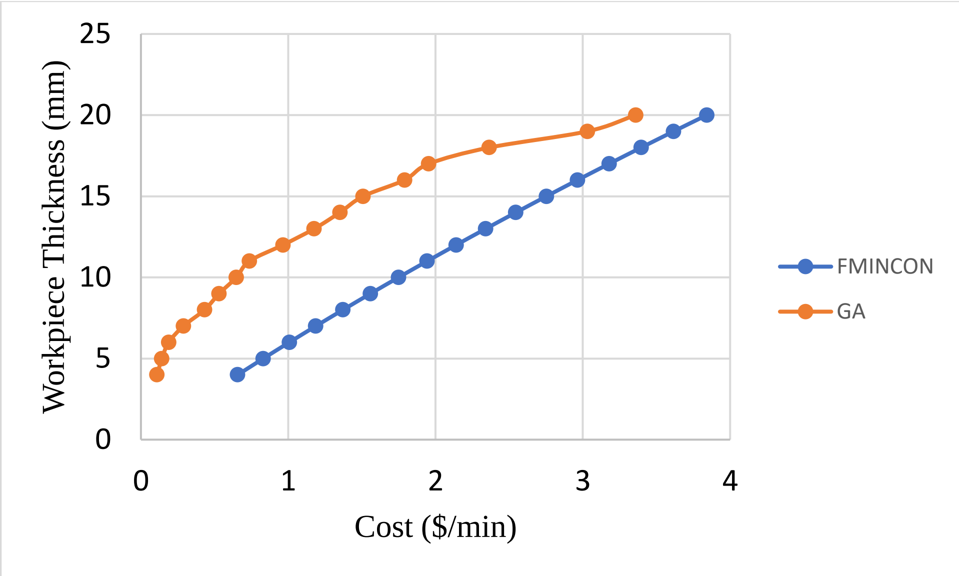

Figure 25: FMINCON & GA vs. Cost

3.8 Summary

In order to compute minimum cycle time and minimum cost for an operation at AWJM, two algorithms were proposed. Both FMINCON solver and genetic algorithm minimized objective functions for time and cost. Even though by nature they are different algorithms, it was seen that the results obtained were not significantly different from one another. Considering the fact that GA has randomness in its nature, FMINCON solver may be more reliable in terms of resulting with more on point solutions. It is important to mention that GA has multiple sub-optimal solutions. Therefore, in order to reach the correct result, the algorithm may require to be solved repeatedly. To avoid this, FMINCON solver will give a more direct result as long as an initial solution and upper/lower boundaries are set correctly.

CHAPTER 4

Metrology in AWJM

AWJM has many benefits compared to conventional machining in terms of chatter and vibration free cutting processes, no heat generation, and being cost efficient, flexible with a large working envelope. Thus, an industrial robot can meet todays and tomorrows need for a cost-effective, time-effective, yet flexible material processing means. However, even though this industrial robot has several advantages compared to conventional machine tools, there is still room for improvements. One of the most significant drawbacks of AWJM is that tapering occurrence in operations and the lengthy cycle time of the process.

This section aims to measure the geometrical features of prismatic and simple parts, such as perpendicularity and flatness. In addition to this, the accuracy and precision capabilities according to the parts that have been machined using the AWJ robot will be examined. The AWJ robot that was has machined the parts is KUKA 16-2 C-F robot. It is important to decide whether the dimensional accuracy that is given by the robot can be achieved by measuring non-complex shapes.

4.1 Measurements

Two parts are machined by the abrasive water jet: one cylinder and one rectangular prism. The measurements were done by both CMM and a calliper.

4.1.1 Rectangular Prism

The first part to be considered is the rectangular prism. This shape was machined with intended measurements of 46.8 * 28.9 * 13 mm. Perpendicular edges were measured 5 times by calliper, both from upper and lower part of the rectangular prism. In order to claim the perpendicularity, it is a must for opposite edges to have equal length.

Figure 26: The rectangular prism workpiece

In this case, an average is taken for upper and lower parts of the edges, for each of them. The results are shown below in Table 4.

Table 4: Rectangular prism edge measurements

Edge Number	Upper Edge	Lower Edge	Average
1	46.529	46.566	46.547
2	28.460	28.581	28.52
3	46.422	46.498	46.46
4	28.452	28.482	28.476

If 100 micrometre tolerance is assumed for each measurement, it is possible to say that the edges varied between +/- 100 micrometre range. Meaning that, each opposite edge in the range of the given tolerance. This can be concluded as that the opposite edges are equal to each other, hence this geometric part can be called a proper rectangular prism. In addition to this, perpendicularity can also be commented on. This feature, however, was directly measured by CMM. It resulted that the angles between edges were in 50 micrometre tolerance range, given the measurements in

Table 5.

Table 5: Rectangular prism corner angles

Edge Number	Angle
1-2	89.940
2-3	89.947
3-4	90.054
4-1	90.019

For the perpendicularity, a tolerance of 0.5 degrees is given. From

Table 5 it can be seen that the angles are within the given range. Therefore, both from the measured edges and from the angles in between the edges, it can be concluded that the part has a rectangular shape with perpendicular edges.

It is also important to mention the flatness of the surface. In order to measure this, every part of the surface was touched by the CMM's probe where 8 data points were taken from each part. Tolerance of 50 micrometre was given for the flatness feature. The measurements are given below where it is possible to see that the first two edges are in the tolerance range and the last two are out. However, it is possible to say that this part is adequately flat.

Table 6: Rectangular prism flatness values

Edge Number	Mean of the flatness values
1	0.022
2	0.043
3	0.118
4	0.94

4.1.2 Cylinder

In addition to the rectangular prism, a cylinder was also measured. For this case, a cylinder with diameter 31.25 mm and height 6 mm was considered. For the cylinder, roundness feature was important. Therefore, its diameter was measured at different levels, in order to observe whether the diameters varied at different levels of depth. In this case, the diameter was measured by CMM from the top, middle and bottom part of the cylinder. A tolerance of 100 micrometres were given for this case. The results are given below.

Table 7: Cylinder diameter values

Level	Diameter Value
0 (Top)	31.345
-3 (Middle)	31.333
-6 (Bottom)	31.312

Considering the fact that all levels resulted within the 100-micrometre range it is safe to say that the workpiece is round, even though the diameter is larger than intended.

Figure 27: The cylinder workpiece

4.2 Taper Angle

Due to the nature of AWJM, taper is inevitable. Gupta et al. [30] stated that the top width of kerf is wider that the bottom width, as shown in Figure 28 where Wt is top kerf width and Wb is bottom kerf width.

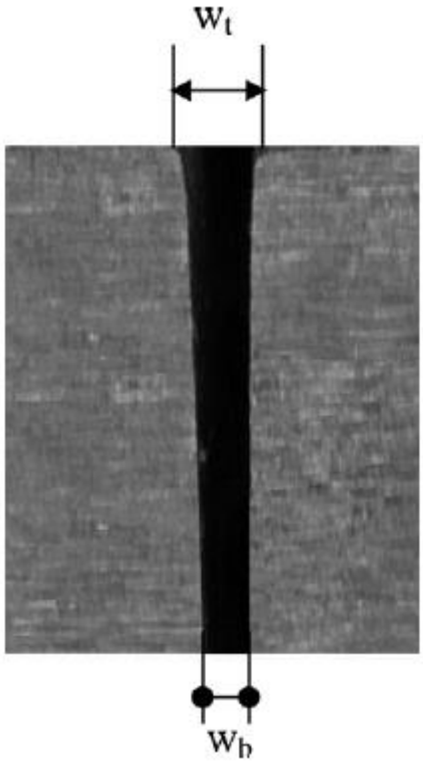

Figure 28: Side view of the kerf [51]

It is possible to compute the taper angle as Hasçalık et al.[51] stated as below.

$$\theta = \arctan\left[\frac{(W_t - W_b)}{2t}\right] \quad (6)$$

where θ is the taper angle, W_t is the top kerf width, W_b is the bottom kerf width and t stands for the thickness of the material. Taper angle is important to be computed correctly since high taper angle causes the flatness or the perpendicularity not to be accurate.

In order to compute the taper angle of the aluminium circle, the diameter was measured from the top and the bottom of the circular part. The measurements are stated as below:

Upper circle (W_t) : 31.345 mm

Lower circle (W_b) : 31.312 mm

Thickness (t) : $6\ mm$

Taking these measurements, the taper angle is computed to be 0.15°. It is important to mention that kerf taper angle is mostly influenced by feed rate, followed by water pressure. Therefore, in order to achieve a certain taper angle, mentioned parameters shall be taken under control. Hence, low feed rate value results in a lower taper angle. Gupta et al.[30] studied in their research that when feed rate was at its lowest possible value at 50 mm/min, kerf taper angle also resulted in being at its minimum value, at 0.32°. The pressure was also chosen as the minimum value at 200 MPa.

This experiment was done at 200 MPa pressure and 25 mm/min feed rate, where the kerf taper angle resulted to be 0.15°. This confirms the fact that for minimum kerf taper angle, it is necessary to have feed rate and pressure at its minimum values, even though there is a trade-off that needs to be solved. Since low feed rate leads to lower productivity, the trade-off between productivity and kerf taper angle is an important aspect to be considered.

4.3 Summary

In this section perpendicularity, flatness and roundness features were investigated of simple geometrical shapes. It was found that abrasive water jet robot is capable of producing parts that are in the range of a given tolerance, while fulfilling the necessities of certain features. In addition to this, kerf taper angle of the cylinder was computed, and the outcome was compared to a previous research. Also, the trade-off between kerf taper angle and productivity was mentioned.

CHAPTER 5

Conclusion and Future Work

The aim of this study was to give an insight to current research about AWJM, a detailed explanation of each process parameter, find the interrelation among the main parameters and suggest a parameter selection approach accordingly. It was concluded that abrasive flow rate had the highest impact on kerf depth, followed by pressure and feed rate. Therefore, the suggested approach was in the light of these observations. SOD effect was significant on kerf width instead of kerf depth, hence it was suggested SOD to be selected as the minimum value. However, this approach was only a starting point. The main goal of the non-linear programming problem was to minimize the cycle time and the total cost. Due to its nature, non-linear problems shall be solved by an algorithm. In this study, both gradient-based and gradient-free algorithms were applied in order to compare the results and make a decision on the superior algorithm. In order to do this, both algorithms were applied. It was seen that minimized cycle time results were more or less the same for both algorithms. For minimized total cost, even though GA results did not have a linear line, both algorithms did not result significantly different from one another. Therefore, it was concluded that in order to minimize the cycle time and total cost in an AWJM operation, both gradient-free and gradient-based algorithms can be used. Although, the random nature of GA must be taken into consideration in this case.

AWJM is a machining technique that has come a long way and still has room for improvement. Even though there are many studies that focused on parameter optimization by different optimization techniques, both minimized cycle time and cost were not studied extensively. In this thesis, FMINCON solver and GA were implemented. However, there are many other algorithms that can be applied in order to find the objectives that are mentioned. This will enlighten the researchers in terms of choosing an algorithm that suits the best for an objective function.

Appendix

Test No	Feed	Pressure	SOD	Abrasive Rate	Average			Depth of cut
	mm/min	MPa	mm	g/s	ch_1	ch_2	ch_3	
1	500	350	2	2	7.982	7.69	7.91	7.860667
2	1000	350	2	2	5.316	4.992	5.166	5.158
3	2000	350	2	2	2.546	2.842	2.682	2.69
4	3000	350	2	2	2.092	2.184	2.032	2.102667
5	6000	350	2	2	1.006	1.07	1.214	1.096667
6	500	250	2	2	8.104	7.228	8.48	7.937333
7	1000	250	2	2	5.062	5.09	5.126	5.092667
8	2000	250	2	2	2.762	2.578	2.642	2.660667
9	3000	250	2	2	2.242	1.988	1.994	2.074667
10	6000	250	2	2	1.39	1.708	1.46	1.519333
11	500	200	2	2	8.528	7.75	8.066	8.114667
12	1000	200	2	2	5.524	5.112	5.244	5.293333
13	2000	200	2	2	2.784	2.724	2.96	2.822667
14	3000	200	2	2	1.878	1.862	1.746	1.828667
15	6000	200	2	2	1.65	1.712	1.618	1.66
16	500	200	2	2	8.466	8.646	8.436	8.516
17	1000	200	2	2	5.294	5.528	5.51	5.444
18	2000	200	2	2	3.156	3.054	2.958	3.056
19	3000	200	2	2	1.718	2.01	2.024	1.917333
20	6000	200	2	2	1.62	1.322	1.414	1.452
21	2000	350	2	2	2.656	2.874	2.848	2.792667
22	2000	350	2	4	2.196	2.052	2.738	2.328667
23	2000	350	2	5	0.496	0.666	1.514	0.892
24	2000	350	2	7	0.292	0.258	0.25	0.266667

Test No	Feed	Pressure	SOD	Abrasive Rate	Average			Depth of cut
	mm/min	MPa	mm	g/s	ch_1	ch_2	ch_3	
25	500	350	2	2	6.296	6.482	6.546	6.441333
26	500	350	2	4	7.748	8.17	8.244	8.054
27	500	350	2	5	9.886	10.386	9.58	9.950667
28	500	350	2	7	7.544	7.802	8.85	8.065333
29	500	350	4	2	8.96	9.866	9.886	9.570667
30	1000	350	4	2	5.3	5.496	5.206	5.334
31	2000	350	4	2	2.894	2.848	2.914	2.885333
32	3000	350	4	2	1.856	2.18	2.08	2.038667
33	6000	350	4	2	1.37	1.308	1.98	1.552667
34	500	350	6	2	9.038	9.452	9.422	9.304
35	1000	350	6	2	5.42	5.714	5.974	5.702667
36	2000	350	6	2	3.004	2.656	3.132	2.930667
37	3000	350	6	2	2.182	1.892	2.04	2.038
38	6000	350	6	2	1.166	1.664	1.668	1.499333
39	500	100	2	2	0.902	0.294	0.484	0.56
40	1000	100	2	2	0.314	0.276	0.252	0.280667
41	2000	100	2	2	0.198	0.262	0.25	0.236667
42	3000	100	2	2	0.208	0.2	0.31	0.239333
43	6000	100	2	2	0.228	0.198	0.198	0.208
44	500	350	2	2	9.496	9.086	9.51	9.364
45	1000	350	2	2	5.306	5.614	5.824	5.581333
46	2000	350	2	2	2.716	2.8	2.684	2.733333
47	3000	350	2	2	1.894	1.626	1.78	1.766667
48	6000	350	2	2	1.212	1.788	1.14	1.38

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