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Study of Influential Process Parameters in Abrasive Water Jet Machining of Aluminium 6061-T6 Alloys

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ABSTRACT:

In this investigation, Abrasive water jet machining (AWJM) has been employed to machine the AA6061-T6 alloy and attempts have been made to evaluate the effect of various process parameters like water jet pressure, abrasive flow rate, stand-off-distance and traverse speed, which are responsible for the cut quality, surface finish and efficiency of machining. The Taguchi design of experiments (DoE) technique has been applied to investigate the material removal rate, surface roughness and hardness as response characteristics. Multi-parametric optimisation using the response surface methodology is established to enhance the efficiency and effectiveness of the AWJM.

KEYWORDS:

Abrasive water jet machining; AA6061-T6; Design of experiment; Material removal rate; Surface roughness; Hardness

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1. Introduction

As a result of its exceptional composite characteristics, aluminium is among the most versatile, practical and correction-resistant materials. Aluminium alloys are an excellent supplemental material because of their sensitivity and malleability, which make them second only to steel in the most challenging engineering applications. Aluminium alloys have found widespread application in design due to their many desirable qualities, such as their high strength-to-weight ratio and outstanding corrosion resistance. It is also possible to inexpensively split the aluminium alloy components into segments of different forms. Among the many potential segments, channel segments have been more frequently used in development projects due to their ease of association, high reliability and smooth, sleek shapes [1]. Abrasive water jet machining (AWJM) is now considered a cutting-edge alternative to traditional processes in the industrial processing of materials. This is because of the multiple benefits, such as the lack of thermal distortion, minimum cutting pressures and enhanced flexibility. These properties make the material removal using water droplets is a better quality and cost-effective process than conventional and some non-conventional processes. AWJM is used on various materials such as titanium, steel, aluminium, brass, Inconel, glass, composites [2]. AWJM is necessary while working with aluminium because it enables precise cutting without any metal deformation by heat. Conventional machining methods leave a heat-affected zone as the thermal conductivity of aluminium is high. These zones can change a material's microstructural and mechanical properties, leading to reduced strength and failure in performance.

AWJM got its advantage for milling aluminium with required quality and accuracy [3, 4]. AWJM employs fewer cutting forces than conventional machining processes, thus resulting in lesser energy consumption that meets sustainable production system requirements and lowers the operational costs. Therefore, increasing demand for high-performance, eco-friendly production systems in different industrial sectors has provided solutions at higher productivity levels using AWJM for milling aluminium components [5]. Aluminium alloy is utilised as the matrix material to produce metal matrix composites (MMCs). The aerospace and automotive sectors increasingly recognise these composites' value due to their exceptional strength-to-weight ratio. Prabhuswamy et al [6] investigated the influence of various input parameters, such as abrasive mass flow rate, water jet pressure and traverse speed of the jet, on the depth of cut of AA6061. The specimens were cut into trapezoidal forms using a mix of water jet and garnet abrasives with a mesh size of 80. Utilising grey-fuzzy logic to optimise the AWJM settings improved the pace at which material is removed and the roughness of the surface of the AA6061-T6.

Machine learning models apply forward and reverse modelling techniques for various machining operations to estimate input parameters and response values. This modelling method produces machining response and therefore, reduces the trial-and-error need in determining the process parameters, saving time and effort [7]. Cutting speed and material thickness greatly influence the kerf taper, while water pressure and abrasive flow have less effect. The kerf's taper decreases with a decrease in cutting speed as material thickness increases [8]. The S235JR carbon steel structure underwent localized alterations due to high energy concentration in the region of the abrasive water jet cut. Heat is perceived as a method of energy transfer into a substance. This is especially true for thick materials with a high thermal conductivity coefficient when cut at moderate velocities or with heavy abrasive use. The temperatures at the edges may be significantly greater. The X-ray diffraction qualitative phase analysis suggests that local temperatures may be substantially higher than eutectoid [9]. Thamizhvalavan et al [10] studied the material removal rate (MRR), roughness and depth of cut for the variation in the water pressure, nozzle speed, abrasive feed rate and mesh size in the cutting tests of aluminium-boron carbide-zirconium silicate hybrid MMCs with Al 6063. Surface topography and morphology descriptions were used to conduct the complete evaluation studies. It was found that the machinability and surface quality aspects of Al6063 are affected by the proportion rate of B_4C with $ZrSiO_4$ ceramic particles. Higher depth of cut, MRR and lower roughness in MMCs were also attributed to the abrasive mesh size.

Shanmugam et al [11] found the best multi-response AWJM for Al7075 MMCs. They used Taguchi's L9 orthogonal array and looked at pressure, standoff distance and movement speed as AWJM factors. Surface roughness (Ra) decreased by 5.4% and the taper angle decreased by 10.9% after optimization. The significance of particles reinforced MMCs is growing due to their distinctive properties. These composites are rigid to machine because of their strength. Manoj et al [12] delved into process parameter effects on AWJM of TiB_2-reinforced Al7075 composite. Taguchi-DEAR is a technique that uses water jet pressure, transverse speed and standoff distance to assess the machining process's MRR, Ra and taper angle. The experimental results show that water jet pressure had more significant effect on the performance characteristics of the AWJM process when determining impact energy. One benefit of AWJM when cutting aluminium components is sufficient freedom and flexibility. This process is relied upon by aerospace, automotive and electronic companies to cut detailed shapes and intricate drawings with superb accuracy.

Conventional machining methods, especially on soft, slender aluminium parts, cannot handle such complexities. By generating smooth edges without burrs, AWJM reduces production costs and eliminates the need for post-processing operations. The ability to produce customised aluminium components according to specific requirements makes it as the most preferred choice [13]. Namlu et al [14] investigated how water jet pressure (WJP), abrasive flow rate (AFR), stand-off distance (SoD) and traverse speed (TS) affect the cutting process of AA6061-T6 alloy utilizing AWJM. It is essential to adjust the operational settings of an abrasive water jet machine to improve the surface quality, hardness (HD) and MRR for work specimens. Utilizing fractional factorial design with Plackett-Burman design under the design of experiments helps to enhance the parameters for machining of AA6061-T6 alloy.

2. Materials, methods and experiments

AA6061-T6 is a vital aluminium alloy with widespread industrial usage due to its high strength and flexibility. Its major components are silicon (0.4-0.8%), magnesium (0.8-1.2%) and aluminium (0.8-1.2%); iron, copper, manganese, chrome, zinc and titanium make up smaller portions. The AA6061's balanced composition makes it strong, corrosion-resistant and workable. With its improved mechanical qualities brought about by solution heat treatment and artificial ageing, it achieves the T6 temper, making it highly desired for various demanding applications. The ultimate tensile strength of 290MPa, the yield point of 240MPa and the HD of 95BHN are attained with T6 heat treatment [14]. Low density of 2.70 g/cm³ combined with high strength makes AA6061-T6 for extensive use in aerospace components such as fuselage frames or wings [15]. An abrasive water jet cutting machine was used to conduct the experimental testing on a 50 mm square block of 500 mm length of AA6061-T6 alloy. Metrics for the X-Y motions of the AWJM are 300mm and 1500mm along the X and Y axes respectively. AWJ machine had a hopper that received the abrasive material through gravity. The orifice diameter is 0.30 mm and the nozzle focusing diameter is 0.60mm. The abrasive used is garnet with a mesh number of 80. In this research, the Plackett-Burman design (PBD) was utilised to investigate the influential process parameters in AWJM.

PBD, a subset of fractional factorial design, operates on the principle that main effects can be accurately estimated with fewer experiments by disregarding interactions. Typically, in a Plackett-Burman analysis, the main effects are associated with 2-factor interactions, as seen in resolution III screening designs. Table 1 details the process parameters and their respective factors. Assuming that interactions and higher-order terms are negligible and uncorrelated, it can estimate only the significant effects with high precision. The process parameters examined in this study include AFR, WJP, TS and SoD. These parameters influence the Ra, HD in BHN and MRR in g/min, which are the critical output responses in AWJM. Using Minitab 19 to implement PBD with high and low values for each parameter, 12 experimental runs were conducted. The samples were machined under these conditions, as illustrated in Fig. 1. The results for Ra, HD and MRR are presented in Table 2. The contour plot generation is facilitated by the formation of the regression equations through PBD as,

$$\mathrm{MRR} = 5.137 + 0.00052\ \mathrm{AFR} - 0.00137\ \mathrm{WJP} + 0.00392\ \mathrm{TS} - 0.015\ \mathrm{SOD}$$

$$\mathrm{Ra} = 5.13 - 0.00040\ \mathrm{AFR} - 0.00132\ \mathrm{WJP} + 0.0040\ \mathrm{TS} - 0.103\ \mathrm{SOD}$$

$$\mathrm{HD} = 94.8 - 0.0133\ \mathrm{AFR} + 0.0533\ \mathrm{WJP} - 0.1167\ \mathrm{TS} - 0.00\ \mathrm{SOD}$$

Table 1: AWJM process factors and its levels

AWJM factor	Unit	Low	High
AFR	g/min	300	400
WJP	MPa	250	300
TS	mm/min	40	60
SoD	mm	2	3

Fig. 1: AWJM samples of AA6061-T6

Table 2: Experimental results of AA6061-T6

Std order	Run order	AFR	WJP	TS	SOD	Ra	MRR	HD
9	1	300	250	40	3	4.32	5.12	97
12	2	300	250	40	2	4.98	4.95	101
4	3	400	250	60	3	4.27	5.23	94
1	4	400	250	60	2	4.90	5.5	98
7	5	300	300	60	3	4.29	4.98	102
6	6	400	300	60	2	4.53	4.91	95
2	7	400	300	40	3	4.42	5.23	103
3	8	300	300	60	2	4.79	5.16	101
10	9	400	250	40	2	4.27	4.95	99
8	10	300	250	60	3	4.90	5.06	97
11	11	300	300	40	2	4.27	5.18	100
5	12	400	300	40	3	4.93	4.94	101

3. Results and discussion

The contour plots of Ra are shown in Fig. 2. As the WJP increases, the Ra tends to decrease because the high-pressure water jet smoothens the surface and removes the material. The contour patterns display the most favourable WJP intensities that lead to the lowest Ra values, resulting in smoother surfaces. It is essential to understand this linkage to adjust the WJP parameters so that the Ra is of high quality and the material disintegration is minimised, thus leading to increased efficacy and efficiency in the AWJM process. In addition, the contour plots which show Ra against the SoD give an insight into Ra effects on the samples. As the SoD moves up, there is an increase in Ra which is caused by less precision and force application at large distances. On the contrary, if the SoD reduces, it will have lower Ra values because, at short distances, it is more concentrated and effective. Contour patterns can help one to determine proper SoD values for low Ra, which results in smoother surface creation. This analysis is essential to make maximum use of AWJM processes since it emphasises how vital its precise control is for getting high-quality surfaces [12], [16]. The contour plots of Ra with AFR and TS further elucidate the variables that influence the Ra in the AWJM process. Generally, the Ra is decreased by the polishing action and material removal by the abrasive particulates with an increase in AFR. Similarly, Ra values are usually lower for the case of a higher TS, which is the fact that reduced time for tool-material interaction is responsible for smoother surfaces. On the other hand, Ra increases by decreasing TS since the instrument has more time to work on the surface, which could create rougher textures and more material removal. From an analysis of these interactions, an operator can configure both AFR and TS for optimum performance in machining, ensuring the attainment of the intended surface quality and elongating the tool's life [13].

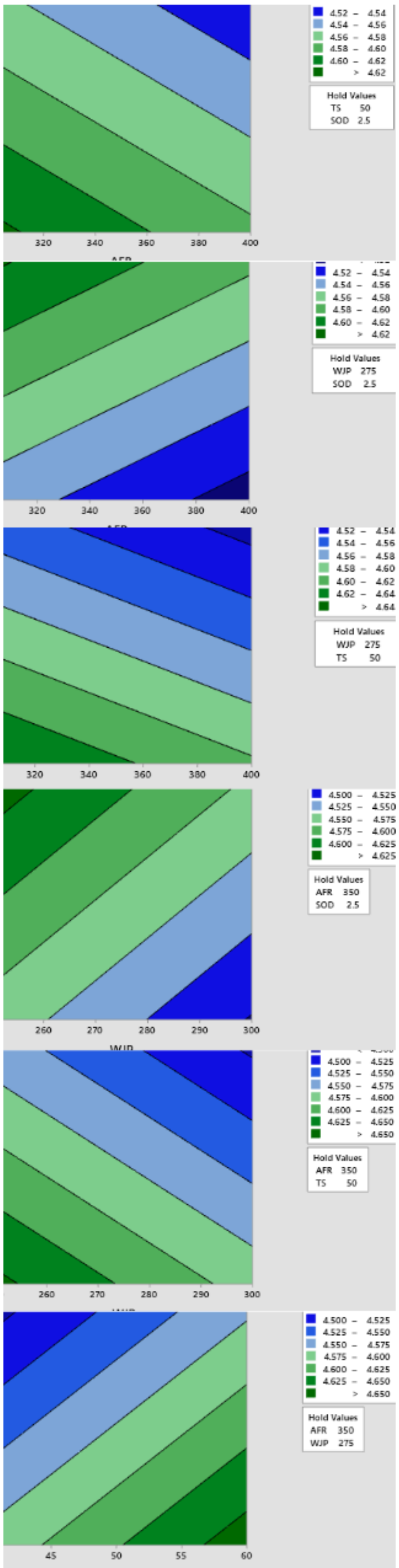

Fig. 2: Contour plots of Ra response

Fig. 3 shows an influential contour plot of MRR with AWJM process parameters. Material removal efficiency can be improved with increased pressure, as is typically evident from the increase in MRR with WJP. On the other hand, the contour lines also show areas of declining returns where, increasing the pressure further gives minor improvements in MRR. Moreover, the profiles could also indicate optimum pressure settings that maximise MRR while minimising negative consequences, such as cutting tool wear or material distortion. This acquired knowledge may considerably improve the water jet machining processes towards achieving the removal of material more effectively with less exposure to tools and materials [15], [17]. Similarly, contour plots of MRR concerning AFR can give critical insights into how changes in AFR impact MRR during machining. There is an increase in MRR as the AFR increases, probably because a higher flow rate for abrasives enhances the material removal efficiency. On the other hand, contour lines indicate areas where an increase in AFR results in levelling off or even a drop in MRR, indicating the ideal range of AFR for optimum efficiency. This interaction identifies the importance of proper abrasive flow balance to avoid unnecessary wear of the tools and ineffective material removal. A complicated relationship between SoD and MRR is usually noted, wherein at short distances, MRR increases and at greater distances, it plateaus or declines. Increasing the SoD improves cutting efficiency through a better flow and impact of abrasives; too much SoD lowers the cutting efficiency by spreading the energy and abrasive over a greater area, hence the lowering of its effectiveness in cutting. These relationships enable an operator to try out different SoD settings for optimum performance in machining [18, 19].

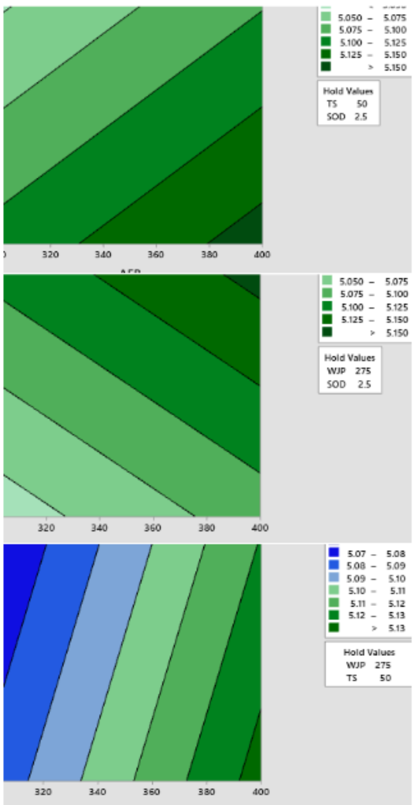

Fig. 3: Contour plots of MRR response

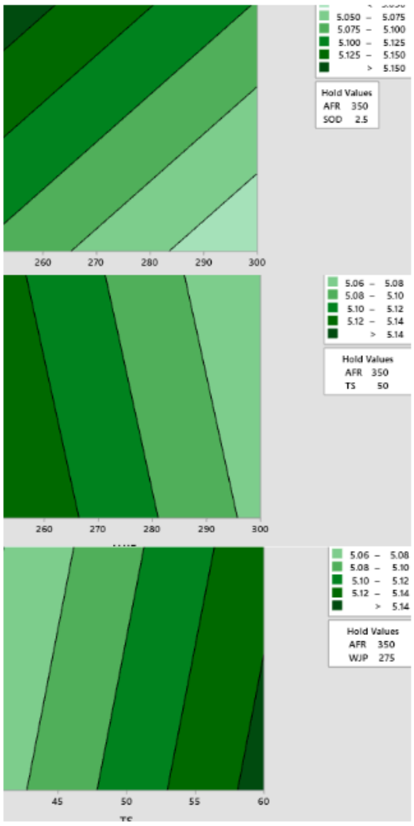

Fig. 3(contd.): Contour plots of MRR response

Fig. 4 shows that the contour plots assess HD with varying AWJM processing parameters. With decreasing WJP values, the HD may sometimes remain more or less constant or fluctuate minimally, suggesting that the WJP is not significant enough to alter the firmness of the material being worked on significantly. Once WJP increases, HD values might start going up. This displays a corresponding growth in the resistance of materials from deformation or penetration by water jets because more force is applied. Regions with abrupt changes between HD and WJP indicate that their relation degenerates at such times. For instance, after reaching a particular level of WJP, one may recognise increased values for HD, implying no linearity between these two variables; this arises due to intrinsic characteristics like elastic behaviour or ductility that come out under high-pressure conditions. Plot diagrams may also assay smoothly all over WJPs, demonstrating challenging areas of less strain to pressure variation from jet streams of water. However, regions with closely spaced contours might indicate areas of high sensitivity, where small changes in WJP lead to significant variations in HD [19-20]. When the values of AFR are low, it is possible to deduce that HD does not vary much, indicating that the AFR is low and will not considerably affect the HD of the material. With the increase in AFR, there may be a slight increase in HD value, which means that materials are less prone to deformation or penetration caused by a higher concentration of abrasive material on their surface. The contour plots might also exhibit critical areas where the relationship between HD and AFR undergoes significant change. For instance, there could be an AFR beyond which steep increases in HD suggest a non-linear relationship between the two variables.

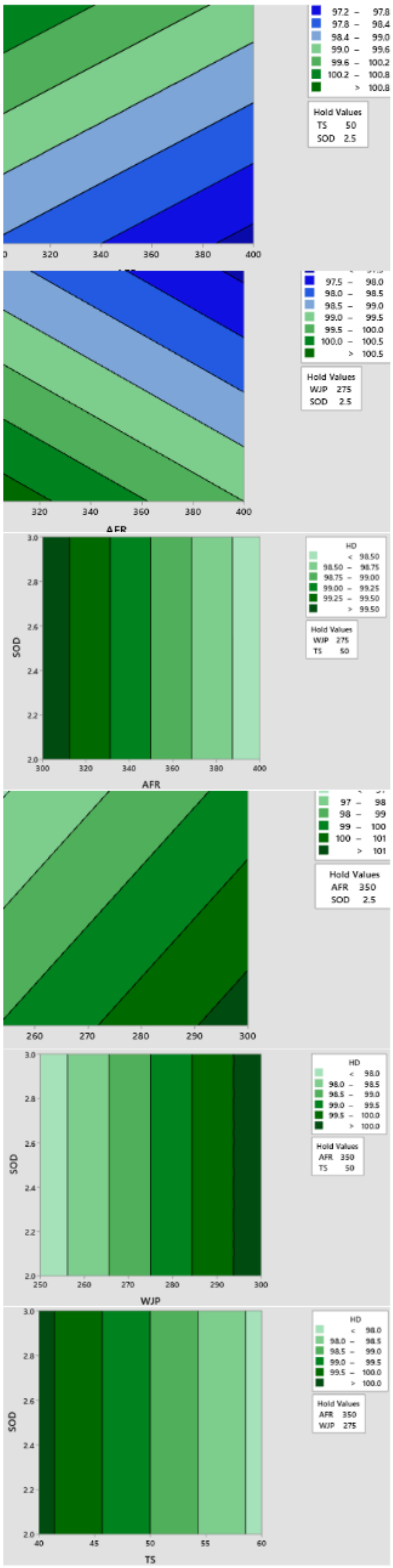

Fig. 4: Contour plots of HD response

At shorter SoD, the HD can be comparably high as a result of increased force applied onto the surface of the materials by water jets. Also, TS are very critical when it comes to defining HD values. An increase in HD could occur at a lower range of speeds because there is ample time for interaction between a water jet and materials. These contour maps may reveal crucial points or regions with abrupt changes in HD related to SoD and TS. A specific combination set could exist by which standoff distances match with travelling speeds at which hardening becomes rapid, suggesting a non-linear relationship between them. This might be connected to pressure and time effects on material deformation during impact loading. On the other hand, closely spaced contour regions might indicate high sensitivity areas where even slight alterations in walking or discharging velocity significantly impact HD values [17], [21].

The optimisation plot of response (Fig. 5) exhibits a visual display of three critical responses: HD, MRR and Ra affect AFR, WJP, TS and SoD. The parameters are optimised to achieve the desired results. The optimal value for AFR is 400 g/min, implying that higher abrasive flow rates positively influence the response. A balanced pressure that maximises HD and MRR while minimising Ra can be obtained through an optimal WJP of 300 MPa. The optimal TS of about 44.04 mm/min efficiently balances the MRR with the surface quality. The optimal SoD value of 3mm shows that this distance aids effective material interaction, thus improving the overall performance. Regarding the responses, the maximum HD achieved is 100.3620 BHN with a desirability (d) of 0.70688, indicating that the chosen parameter settings are effective for achieving high HD levels. The maximum MRR achieved is 5.0617 g/min, with a desirability (d) of 0.25705, suggesting room for further optimisation to improve MRR. The minimum Ra achieved is 4.4433, with a desirability (d) of 0.75380, indicating that the settings effectively reduce Ra. The composite desirability (D) is 0.5155, reflecting moderate overall parameters optimisation across all responses. Although the present settings strike a decent balance, further tweaks could improve overall performance, according to this composite desirability score.

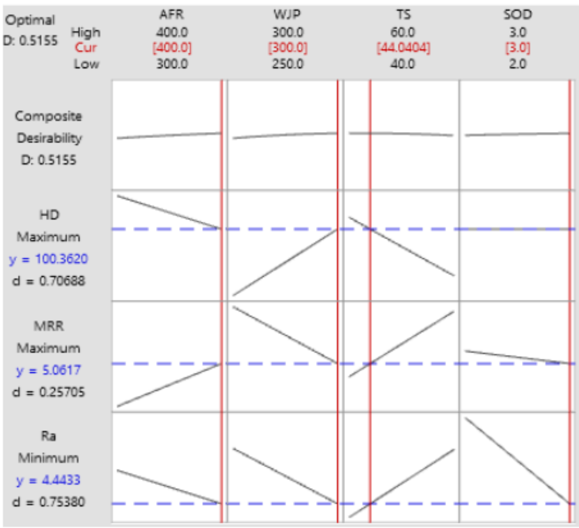

Fig. 5: Optimization results of process parameters of AWJM

4. Conclusion

A practical approach to cutting aluminium is AWJM, particularly with AA6061-T6, which reduces the heating effect on the material and maintains its structural integrity. This study employed the design of experiments to examine the influence of WJP, AFR, TS and SoD on

Ra, MRR and HD of AA6061-T6 machining. The response optimisation plot indicates that the best parameters for AWJM are AFR of 400g/min, WJP of 300 MPa, TS of 44.04 mm/min and SoD of 3 mm. Due to these factors, HD, MRR and Ra improved. The HD peaked at 100.3620 BHN and the MRR was 5.0617 g/min. In contrast, the attained Ra was recorded as 4.4433 Ra, indicating that selected parameter values effectively improved the Ra.

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