Experimental Investigation on Cryogenic Assisted Abrasive Aqua Jet Machining of Die Steel

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This paper reports the investigation on parametric optimization of the abrasive aqua jet (AAJ) and cryogenic assisted abrasive aqua jet (CAAAJ) processes for cutting AISI D2 steel using multi objective TOPSIS approach. The input parameters considered were aqua jet pressure, abrasive grit size and jet impingement angle. In this study, depth of penetration, metal removal rate, kerf taper ratio and average roughness were taken as the performance characteristics. The results showed that the CAAAJ process exhibited better performance characteristics than the AAJ process. The AAJ machining process with an inclined jet impact angle influences the output responses, which is evident from an optimal selection of parameters. Besides, the influencing process variables were determined by using the analysis of variance. The overall machining performance of the AAJ and CAAAJ processes were improved by using the optimum process variables through the TOPSIS method.

Keywords : *Abrasive Aqua jet, Cryogenic, Cutting, Die steel, performance features, TOPSIS.*

1. INTRODUCTION

Cryogenic assisted machining is a modern method applied for machining hard materials using low temperature liquids. Low temperature liquids are called cryogenics. Cryogenics have distinct characteristics such as harmless, odourless, and colourless. They also improve the properties of the materials through the application of low temperature liquids [1-3]. Many thermal assistance techniques were developed in machining processes so far. However, more attention is received from the cryogenic assisted machining techniques, including conventional and unconventional, as the maintenance of stability in material surface and dimensional features. Researchers have also employed a cryogenic system in an abrasive aqua jet (AAJ) with different set up routes, such as cryogenic jet machining with replacement of aqua and abrasives using cryogenics (carrier fluid), and abrasive cryogenic aqua jet with substitution of traditional abrasives [4].

AAJ removes the material through the mechanical erosion process by using a high velocity of abrasive aqua jet impact over the target materials. It is well known for the less heat affected zone and better dimensional stability [4]. However, the modified techniques were developed for the reduction of existing limitations on the AAJ process such as the higher volume of secondary wastage, heat developed at the sensitive zone, abrasive embedment, waviness formation, poor surface finish and poor energy transfer which cause a low penetration depth, low metal removal rate, poor taper angle, surface alteration etc [5]. Due to this, the use of the AAJ machining tool was restricted in the manufacturing industries. The main aim of the cryogenic development is to offer better performance by changing the work material phases at a lower temperature. This phase change allows the erosion process with a favourable mechanism and yields better process attributes [6-7].

However, there has been minimal work in the field of cryogenic assisted abrasive aqua jet (CAAAJ) machining of AISI D2 Steel [8]. Owing to the number of machining parameters involved in the aqua jet machining process, significant improvements in the machining performance can be achieved by optimizing the process parameters. In the previous work on optimization, the Taguchi method played an essential role in enhancing quality and productivity at a minimum cost. It was utilized for optimizing a single performance characteristic. However, further research is needed for handling multi objective performance characteristics. The determination of the optimal process variables for AAJ and CAAAJ machining processes is a tough task as that processes are involved with multi objective performance characteristics. Therefore, it requires the suitable multi criteria decision making method (MCDM) to optimize the process variables.

Numerous decision arriving methods are available in MCDM, such as Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity Ideal Solution (TOPSIS), Elimination and Et choice Translating reality (ELECTRE) I, II, III, VIKOR and grey relational analysis, involved in engineering problems. Authors themselves have used the TOPSIS and the Grey techniques in AAJ machining of Aluminium alloy [9] and die steel [10]. It is observed that those techniques were an effective tool for the process improvement in the AAJ machining process by attaining better optimal settings of process variables. Apart from this, only a few researchers have seen application of the MCDM

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methods for optimal process variables in AAJ for multi response problems. Literature related to single and multi-response optimization of AAJ is briefly discussed below.

Chakravarthy & Babu [11] have optimized the AAJ machining process variables by employing fuzzy logic and genetic algorithm. The outcome indicated that the proposed approach produced a satisfactory performance for achieving the optimum depth of penetration. Jegaraj & Babu [12] have utilized a soft computing method to investigate the machining quality in AAJ machining of 6063-T6 Al alloy. The outcomes showed that a soft computing method producing a consideration of appropriate machining parameters for achieving the preferred machining quality. Srinivasu & Babu [13] have studied the identification of machining parameters in AAJ through the use of neuro-genetic method. This method offered the preferred DOP by varying the focused diameter nozzle.

Caydas & Hascalik [14] have optimized surface roughness in the AAJ machining of AA 7075 aluminium alloy using artificial neural networks (ANN) and regression analysis technique. The analysis of variance (ANOVA) reported that aqua jet pressure had a great impact on average roughness of the machined AA 7075 aluminium alloy, followed by a traverse rate. Azmir et al. [15] developed a mathematical model for optimizing the AAJ process parameters for cutting aramid fibre plastics composites. This model optimized the process parameters for Ra and kerf taper ratio through a single response mode by multiple linear regression analysis. The ANOVA test result found that the traverse rate as the most influencing factor on Ra and kerf taper ratio.

Zain et al. [16] have studied the single response optimization of process variables in AAJ machining of Al 7075 alloy through soft computing techniques i.e. simulated annealing and genetic algorithm. Aich et al. [17] optimized the single response such as DOP by particle swarm optimization technique in AAJ machining of borosilicate glass. Iqbal et al. [18] have investigated on optimal process variables in AAJ machining of AISI 4340 and Aluminium 2219 using the multi criteria numerical optimization technique for simultaneous maximization and minimization of the responses. However, this numerical optimization technique failed to optimize all the responses at a time.

Liu et al. [19] developed the modelling and optimization of process variables in AAJ machining of Aluminium Oxide with an employment of response surface methodology. The predicted result reported that the traverse rate and abrasive mass flow rate were influencing factors on DOP and Ra for AAJ turning process. Azmir et al. [20] utilized an orthogonal array with grey relational method to optimize the AAJ machining process variables in the Kevlar composite. Through, this approach better machining performance were observed in AAJ and the combined improvement in the process parameters. Sathyanarayna & Srikar [21] have studied the optimal settings of process variables for the machining of Inconel through a combination of Taguchi and Grey relational analysis methods. The analysis of variance (ANOVA) results indicated the aqua jet pressure having a highly significant effect on MRR and kerf width.

Sharma et al. [22] studied the selection of AAJ machining variables aimed at enhancing coal production in coal mines with the help of the Taguchi-Fuzzy decision making method. The ANOVA test result indicates a greater effect for traverse rate compared to the output responses. Santhanakumar et al. [23] conducted modelling and optimization of process variables in AAJ machining of ceramics by combined grey relational response surface methodology. Marichamy et al. [24] have optimized the AAJ machining parameters for α-β brass using the taguchi technique. Their results reported that aqua jet pressure was an influencing factor in surface roughness and material removal rate. Kishore et al. [25] investigated the control of taper in AAJ machining of Inconel by using grey relational analysis. The results showed that traverse speed was an influencing factor for the control of kerf taper.

There is no research paper based on the optimization of CAAAJ process parameters. Furthermore, researchers did not periodically report any works on the multi response optimization of the process variables in AAJ by using MCDM techniques. Hence, this study intends to determine the influence of process variables on AISI D2 steel by changing aqua jet pressures, abrasive grit sizes and jet impingement angles under AAJ and CAAAJ machining conditions and their results are examined by using multi objective TOPSIS technique.

2. EXPERIMENTAL SETUP

2.1 Materials and Methods

Figure 1. shows the experimental setup for CAAAJ machining operations. The machining processes were conducted on the injection type OMAX AAJ machining centre. This machine has a maximum aqua jet pressure of 55000 psi and an aqua discharge of 3.2 l/min employed. For the experimental work, wedge shaped AISI D2 steel was selected with a thickness of 80 mm. This work material was chosen based on the cryogenic properties. The variable process parameters taken in to account were aqua jet pressure (175 MPa, 200 MPa, 225 MPa), abrasive grit size (#80, #100, #120), and jet impingent angle (70°, 80°, 90°). These variable process parameters and their levels design the orthogonal array with 27 combinations for the different machining conditions. Also, the other settings were SOD (3 mm), traverse rate (15 mm/min), abrasive mass flow rate (450 g/min), focusing nozzle (0.76 mm), and orifice (0.25 mm). In this study, Garnet abrasive with different grit sizes was employed for cutting operations.

The performance characteristics namely depth of penetration (DOP), material removal rate (MRR), taper ratio and average roughness are taken in to account in this study. The penetration depth was calculated using the equation (1).

$$DOP = L * \sin(\theta) \tag{1}$$

The volume of material removal was measured by the product of depth of penetration, average kerf slot and traverse rate. It is shown in equation (2).

$$MRR = DOP * KWavg * TR \quad (2)$$

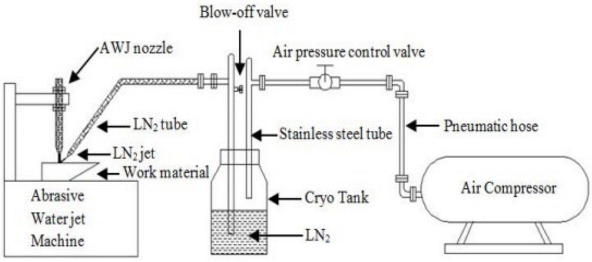

Figure 1. CAAAJ machining setup

Kerf width was measured by using Tool Maker's Microscope with a least count of 0.005 mm. Kerf taper ratio (KTR) was estimated by the ratio of top kerf width to bottom kerf width. Average roughness (Ra) was also measured by using Taly-surf roughness tester. The sampling length and cut-off length were taken as 4 mm and 0.8 mm respectively.

2.2 Data Processing Procedure

In this study, two different MCDM techniques were used for the identification of better optimal settings of parameters for AAJ and CAAAJ machining operations. TOPSIS is a MCDM approach that finds the optimal result from the set of alternatives depend upon the instantaneous miniaturization of distance from an ideal result and longest distance from the lowermost solution. The principle of TOPSIS is to describe a positive and negative ideal result. The positive ideal result is the one which increases the performance measures and decreases the limitations criteria; whereas the negative ideal result increases the limitations criteria and decreases the performance measures. The best alternate is one, which is shortest to the positive ideal result and longest to the negative ideal result.

TOPSIS method needs definite input data from the multi criteria problems for assigning weights to the criteria, which access the comparative significance of multi-criteria for the actual scenarios - Olson [26], Opricovic & Tzeng [27]. For using the weighting criterion, Simos' method was used. In view of the significance of the performance measurements, the decision maker categorizes the variable measurements from the less to the more significant, such as DOP, MRR, KTR, and Ra. The particulars and stages of the Simos' method were noticed by Ozcan et al. [28] and Figueira & Roy [29]. It is an important technique for evaluating real scenarios, and decision makers consider it for numerous causes, namely robustness. It has to generate rapid solutions than the other weighting computational methods. They also tried out the Simos' procedure by using data collection, computational of normalized weights, and minimizing noises by using rounding off the normalized values.

Figure 2. denotes the decision model of the AAJ and CAAAJ machining processes. In this figure, each response was linked to three dissimilar process variables of the jet machining process, and these results were considered to optimize the process variables, through the TOPSIS method.

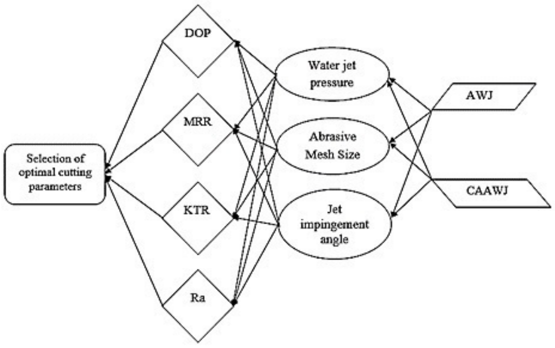

Figure 2. Decision making model of the AAJ and CAAAJ machining processes

2.3 Data Processing Using TOPSIS approach

In this study, Simo's procedure has been applied to determine the most relevant input weights of the output response, and its computational steps are presented as given in Table 1. This procedure calculates weighing of the criteria as follows 1) Definite set of criteria = [DOP, MRR, KTR, and Ra], 2) Criteria (final results) have been set by decision makers based to their significance, from the less to the more significant, such as KTR, Ra and DOP and MRR. In this work, KTR and Ra were taken as different weights; similarly, DOP and MRR. But the decision makers need to improve the significance of the DOP and MRR criteria; so, they put white cards between the two consecutive criteria in the criteria set. Herein technique, white card plays a vital role while allocating the weight of the criteria from the least to the top most important, and the card represents the significance between two consecutive criteria. Putting white cards among the two consecutive criteria implies more weightage or significance to the criteria among all the criteria.

Table 1 Simos weightage of output result

Subset	No. of criteria	No. of positions	Non normalized weighted matrix	Total (%)
KTR	1	1	1/12 = 0.083 ~ 0.08	8
Ra	1	2	2/12 = 0.166 ~ 0.17	17
White card	(1)	(3)		
DOP, MRR	2	4, 5	9/12 = 0.75	75
Total	4	12		100

2.4 Optimization Steps using TOPSIS Approach

The optimization procedure for the TOPSIS method was as follows [26].

Step 1:
The TOPSIS technique is the best ranking technique by selecting the substitutes which eliminate the units of all criteria, and it takes a normalized value. The normalized performance matrix (r_{ij}) values were attained, through the following equation.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{in} X_{ij}^2}} \quad i = 1, 2, ...27; j = 1, 2, ...4 \qquad (3)$$

where, i = no.of substitutes (experimental runs); j = no. of criteria (final results); x_{ij} = normalized value of i^{th} experimental run allied with j^{th} final result.

Step 2:
The weighted normalized matrix (v_{ij}) was determined by the product of the normalized value into the weighted values

$$\vartheta_{ij} = w_j * r_{ij} \quad i = 1,2,......27; j = 1,2,......4 \tag{4}$$

Step 3:
Each output response, the best performance **(S^+)** and the worst performance (S^-) were calculated.
If j^{th} criteria has a better performance

$$S^+ = \left\{\left[\max\left(S_{ij}\right)\middle| j \in J\right] or \left[\min\left(S_{ij}\right)\middle| j \in J'\right], i = 1,2,......27\right\} \tag{5}$$

where, S^+ denotes a positive ideal result; Likewise the S^- values were calculated if j^{th} criteria is worst performance; whereas S^- denotes a negative ideal result.

Step 4:
In this stage, the performance criteria was determined by the best attribute distance (D^+_{ij}) from the positive ideal result (S^+), and worst attribute distance (D^-_{ij}) from the negative ideal result (S^-). The D^+_{ij} and D^-_{ij} values were calculated using equations (6) & (7).

$$D_i^+ = \sqrt{\sum\nolimits_{i=1}^{27}\left(\vartheta_{ij} - S_j^+\right)^2} \tag{6}$$

$$D_i^- = \sqrt{\sum\nolimits_{i=1}^{27}\left(\vartheta_{ij} - S_j^-\right)^2} \tag{7}$$

where i = 1, 2, 3 ….27

Step 5:
The closeness coefficient (C_i) values of each experimental run were determined by using equation (8).

$$C_i = \frac{D_i}{D_i^- + D_i^+} \quad i = 1,2,......27; \le C_i \le 1 \tag{8}$$

The optimum levels were selected as per the preference ranked order by the Ci value, which was nearer to the ideal result.

3. RESULTS AND DISCUSSION

3.1 Optimization of AAJ and CAAAJ Machining Process Variables of AISI D2 Steel

The multi response optimization technique was carried out on machining performance characteristics of AISI D2 Steel under AAJ and CAAAJ machining methods. Table 2 and Table 3 shows the output response values of AAJ and CAAAJ machining conditions for AISI D2 Steel. From the results, it is observed that the CAAAJ machining process increases the machining performance features such as DOP, MRR, KTR and Ra. In the CAAAJ process, the DOP is enhanced by 1.43- 35.93%, owing the decrease in particle entrenching and changeover erosion mechanism in the machining region.

Table 2 L_{27} orthogonal array and process attributes of AAJ

Ex. No	P, MPa	GS, #	IA, deg	AAJ			
				DOP, mm	MRR, mm^3/min	KTR	Ra, µm
1	175	80	70	34.35	327.184	1.57	1.73
2	175	80	80	28.86	294.372	1.42	3.62
3	175	80	90	28.63	362.885	1.46	4
4	175	100	70	26.07	259.462	1.52	1.94
5	175	100	80	29.96	185.153	1.07	1.23
6	175	100	90	33.23	296.079	1.38	4.02
7	175	120	70	23.79	191.985	1.62	2.16
8	175	120	80	26.76	243.449	1.50	2.78
9	175	120	90	23.79	383.257	2.92	1.75
10	200	80	70	43.78	328.022	1.24	2.92
11	200	80	80	44.95	347.576	1.37	1.62
12	200	80	90	40.71	284.258	1.26	2.84
13	200	100	70	45.34	324.748	1.17	2.54
14	200	100	80	42.1	358.376	1.29	2.56
15	200	100	90	40.02	351.326	1.28	2.08
16	200	120	70	39.04	644.892	1.98	1.7
17	200	120	80	38.78	373.742	1.32	2.18
18	200	120	90	34.34	266.564	1.37	1.61
19	225	80	70	53.67	515.232	1.06	2.26
20	225	80	80	45.64	375.092	1.18	2.44
21	225	80	90	43.67	344.163	1.55	2.55
22	225	100	70	47.19	585.746	1.37	1.39
23	225	100	80	43.67	334.731	1.24	1.66
24	225	100	90	38.73	314.584	1.35	2.24
25	225	120	70	42.45	370.589	1.28	1.52
26	225	120	80	40.71	346.849	1.18	1.17
27	225	120	90	36.43	270.493	1.33	1.42

Table 3 L_{27} orthogonal array and the process attributes of CAAAJ

Ex. No	P, MPa	GS, #	IA, deg	CAAAJ			
				DOP, mm	MRR, mm^3/min	KTR	Ra, µm
1	175	80	70	31.6	644.757	1.15	1.55
2	175	80	80	33.84	648.361	1.13	2.8
3	175	80	90	38.7	748.387	1.12	3.54
4	175	100	70	27.17	546.558	1.16	1.46
5	175	100	80	33.43	652.306	1.21	1.3
6	175	100	90	36.92	684.387	1.09	3.34
7	175	120	70	26.7	608.76	1.42	2.06
8	175	120	80	31.74	664.16	1.29	2.1
9	175	120	90	35.14	669.417	1.15	1.28
10	200	80	70	46.01	807.68	1.1	2.24
11	200	80	80	49.8	853.997	1.08	1.5
12	200	80	90	53.68	926.261	1.04	2.56
13	200	100	70	46	775.097	1.13	2.04
14	200	100	80	47.47	854.856	1.11	1.75
15	200	100	90	50.01	872.11	1.05	1.56

Ex. No	P, MPa	GS, #	IA, deg	CAAAJ			
				DOP, mm	MRR, mm^3/min	KTR	Ra, μm
16	200	120	70	40.14	750.953	1.19	1.66
17	200	120	80	40	732.735	1.12	1.54
18	200	120	90	40.54	761.686	1.14	1.32
19	225	80	70	60.48	953.377	1.04	2.12
20	225	80	80	63.28	1051.97	1.04	2.06
21	225	80	90	64.4	1036.04	0.9	2.01
22	225	100	70	54.82	912.329	1.09	1.29
23	225	100	80	58	998.994	1.06	1.45
24	225	100	90	60.45	1078.87	1.03	1.95
25	225	120	70	45.13	819.523	1.14	1.44
26	225	120	80	45.54	793.882	1.07	1.12
27	225	120	90	48.78	885.69	1.09	1.1

Table 4 Closeness coefficient values and their ranking

Ex.No	AAJ		CAAAJ	
	C_i	Ranking	C_i	Ranking
1	0.5637	14	0.5286	20
2	0.4073	25	0.2887	25
3	0.4116	24	0.2372	26
4	0.4908	21	0.5024	22
5	0.5503	17	0.5667	17
6	0.404	26	0.2313	27
7	0.4282	22	0.3867	24
8	0.4243	23	0.4179	23
9	0.3986	27	0.5881	15
10	0.5407	19	0.5279	21
11	0.6432	6	0.7179	8
12	0.5114	20	0.5417	19
13	0.5811	11	0.558	18
14	0.5788	13	0.6532	12
15	0.6078	9	0.7201	6
16	0.6987	3	0.5796	16
17	0.6068	10	0.6019	14
18	0.5576	16	0.6404	13
19	0.7639	2	0.6792	10
20	0.6223	8	0.7196	7
21	0.5426	18	0.7441	4
22	0.8577	1	0.8011	2
23	0.6399	7	0.8331	1
24	0.559	15	0.7425	5
25	0.6676	5	0.6731	11
26	0.6677	4	0.7112	9
27	0.5808	12	0.7624	3
Avg C_i value	0.4419		0.5097	

This cryogenic jet cooling produces a decrease of about 1.72 - 28.40% in the taper ratio and 4.96 - 31.64% minimum average roughness compared to the AAJ machining process. Presence of fine erosion debris in the machining area, the average roughness was reduced through the use of LN_2 cooling in the machining area [6-8]. This result happened increase in hardness of the cut surface offers uniform material removal rate, which yields a better surface finish [8].

The use of cryogenic cooling improves the MRR between the range of 45.96 - 70.84% over the AAJ machining process. Possible modifications in the erosion process of the target material at minimum temperatures cause an increase in the abrasive aqua jet's erosion capability.

3.2. Optimal Parameter Setting

Table 4 shows the coefficient values of each experimental run in association with the Taguchi full factorial design. It is observed that the aqua jet pressure of 225 MPa, abrasive grit size of #100 and jet impact angle of 80^o were produced improved performance features in the CAAAJ machining. Because, it shows that the higher closeness coefficient value and is found to be 0.8331 which is nearby the ideal solution. This optimum variable combination was found at experiment no.23, as shown in Figure 3. This result happens due to the ductile-to-brittle transition zone. It allows the kinetic energy of the abrasive particles to be retained in the lower machining regions with the employment of inclined jet impact angles, and consequently increases the DOP during the machining operations [7-8]. This cryogenic assisted machining leads to reduces particle fragmentation with the target material, and thus the particles retianing their kinetic energy for machining lower cutting region. As a result of this, higher MRR and lower KTR and Ra were observed.

Similarly, the better optimal setting of the AAJ machining were aqua jet pressure of 225 MPa, abrasive grit size of #100 and jet impact angle of 70^o and the corresponding closeness coefficient value is 0.8577. From the results, it is observed that the inclined jet impact angle was contributing a higher kinetic energy than the jet impact angle of 90^o [30]. It is also noticed the abrasive grit size #100 was an optimum level of abrasive rather than the grit size of # 80. It is attributed to that the combination of coarser and finer edges of particles in #100 contributed sufficient cutting energy with a less fragmentation effect.

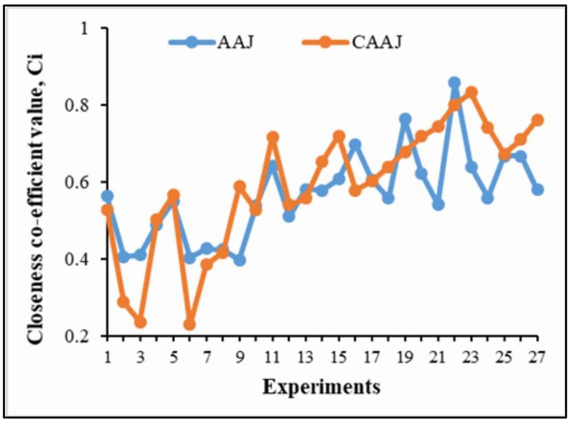

Figure 3. Closeness coefficient values of each experiment

In the present study, ANOVA was performed with 95% confidence level and 5% significant level and the processed values are given in Table 5. From these results, it is observed that an aqua jet pressure was a significant parameter for affecting overall responses of the processes. Because, jet pressure is a prime factor that influences the behaviour of abrasive particles in the mixing process. Figure 4 and 5 shows the contribution of AAJ and CAAAJ process parameters. The CAAAJ ANOVA test outcomes specify that 78.87% of aqua jet pressure, 11.38% of abrasive grit size, 3.84% of jet impact angle, 4.55% of pressure*abrasive grit size, 0.06% of pressure*jet impact angle, and 0.28% of abrasive grit size*jet impact angle were observed is shown in Figure 4. It is also observed that the one-way interaction effects of the pressure, abrasive grit size, and jet impact angle are the salient features for the evaluation of the CAAAJ machining response variables such as DOP, MRR, Kerf Taper Ratio, and Ra. It is understood that the overall contribution of CAAAJ was improved than the AAJ process as that error percentage was 1.02%.

Table 5 Results of ANOVA for AAJ and CAAAJ machining of AISI D2 Steel

Factors	DOF	Sum of squares	Mean squares	F-test	P-value	% of contri-bution
AAJ						
P	2	0.55149	0.27574	90.72	0.000*	65.32
GS	2	0.05291	0.02645	8.70	0.010*	6.27
IA	2	0.03499	0.01749	5.76	0.028*	4.15
P*GS	4	0.02231	0.00558	1.84	0.215	2.64
P*IA	4	0.15456	0.03864	12.71	0.002*	18.31
GS*IA	4	0.00358	0.00089	0.29	0.874	0.43
Error	8	0.02431	0.00303			2.88
Total	26	0.84419				100
CAAAJ						
P	2	1.09265	0.54632	308.34	0.000*	78.87
GS	2	0.15770	0.07885	44.50	0.000*	11.38
IA	2	0.05330	0.02665	15.04	0.002*	3.84
P*GS	4	0.06302	0.01575	8.89	0.005*	4.55
P*IA	4	0.00073	0.00018	0.10	0.978	0.06
GS*IA	4	0.00379	0.00094	0.54	0.714	0.28
Error	8	0.01417	0.00177			1.02
Total	26	1.38539				100

*Significant factors

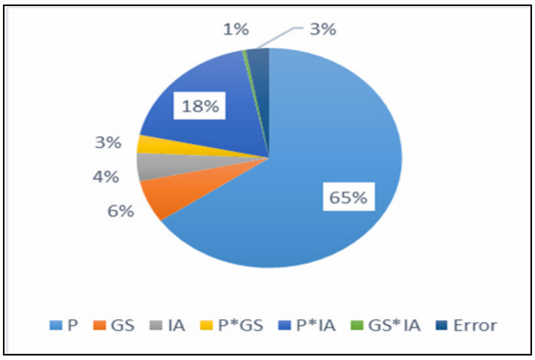

Figure 4. AAJ - Process parameter influence by percentage

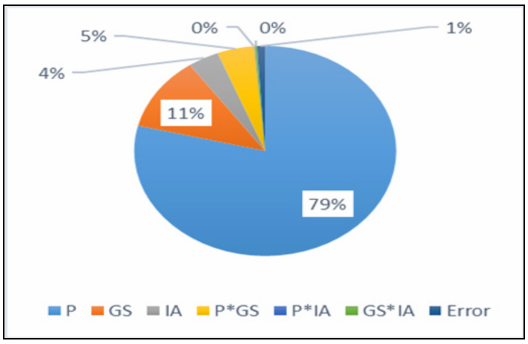

Figure 5. CAAAJ - Process parameter influence by percentage

However, the jet impact angles and their interaction effects contribute less percentage over the AAJ and CAAAJ processes. It is also noticed that the two-way interaction combinations had a less influencing role in the CAAAJ machining of the AISI D2 steel.

3.3 Results of the optimum machining Variables

Table 6 shows the optimal machining parameters for AAJ and CAAAJ cutting of die steel. The output responses of CAAAJ such as the DOP 64.40 mm, MRR 1036.04 mm^3/min, KTR 0.9 and Ra 2.01 µm were found at the aqua jet pressure of 225 MPa, abrasive grit size of # 80, and jet impact angle of 80°. These attributes were better than the AAJ process. Therefore, it is confirmed that the CAAAJ process outperforms the AAJ process.

Table 6 Results of the optimal machining parameters for AISI D2 steel

Best parameters setting		
	CAAAJ	**AAJ**
Setting level	P3, MS1, IA3	P3, MS1, IA1
Aqua jet pressure	225 MPa	225 MPa
Abrasive grit size	#80	#80
Jet impact angle	90°	70°
DOP, mm	64.40	53.67
MRR, mm^3/min	1036.04	515.232
KTR	0.9	1.06
Ra, µm	2.01	2.26

4. CONCLUSION

The major results are concluded below.

1. The CAAAJ process improves the DOP and MRR by the reduction of particle contamination with the cut surfaces through the changeover erosion process in the machining zone [8].
2. Cryogenic assisted jet machining provides a decrement in the KTR and Ra over the AAJ machining process.
3. In AAJ and CAAAJ, the inclined jet impact angles have more influence on the performance characteristics. Also, the jet impact angles of 70° and 80° with different abrasive grit sizes influence the AAJ machining process.
4. By using TOPSIS method, the aqua jet pressure of 225 MPa, abrasive grit size of #80 and jet impact angle of 80° was found to be optimal process parameters for CAAAJ machining. Similarly, the better optimal process parameters found in AAJ machining such as aqua jet pressure of 225 MPa, abrasive grit size of #100 and jet impact angle of 70°.
5. ANOVA results confirmed that aqua jet pressure, abrasive grit size, jet impact angle, and interaction effects of aqua jet pressure and jet impact angle were the most significant factors in CAAAJ machining of AISI D2 Steel. It is also observed that, the aqua jet pressure, abrasive grit size, jet impact angle and the interaction effect of the aqua jet pressure and abrasive grit size are the significant factors in the AAJ machining of AISI D2 Steel.

6. In AAJ and CAAAJ processes, aqua jet pressure was found as a most influencing factor and followed by abrasive grit size and jet impact angle on the process attributes.

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REFERENCES

[1] Natasha, A.R., Ghani, J.A., Haron, C.H.C. and Syarif, J.: The effect of cryogenic application on surface integrity in manufacturing process: a review. J Appl Sci Res, Vol. 8, No. 9, pp. 4880–4890, 2012.

[2] Kumar, S., Bongale, A. Khedkar, N.: Machining Performance Evaluation of Liquid Nitrogen Treated M2 Cutting Tools for Turning Operations. FME Transactions, Vol. 48, No. 1, pp. 227-235, 2020.

[3] Ahmed, L.S., Yuvaraj, N. and Hariprasad, T.: Influence of Cryogenic Reaming Process Parameters on Titanium Alloy by Using Grey Relational Analysis. FME Transactions, Vol. 47, No. 3, pp. 634-640, 2019.

[4] Natarajan, Y., Murugesan, P.K., Mohan, M. and Khan, S.A.L.A.: Abrasive Water Jet Machining process: A state of art of review. J Manuf Processes, Vol. 49, pp. 271-322, 2020.

[5] Yuvaraj, N.: *Experimental Investigations on Cryogenic assisted abrasive water jet machining of aluminium alloy and die steel,* Ph. D Thesis, Faculty of Mechanical Engineering, Anna University, Chennai, India, 2017.

[6] Yuvaraj, N. and Kumar, M.P.: Cutting of aluminium alloy with abrasive water jet and cryogenic assisted abrasive water jet: A comparative study of the surface integrity approach. Wear, Vol. 362-363, pp. 18-32, 2016.

[7] Natarajan, Y., Murugesan, P.K., Sundarajan, L. and Arunachalam, R.: Experimental Investigation on Cryogenic Assisted Abrasive Water Jet Machining of Aluminium Alloy. Int J Precis Eng Manuf-Green Tech, Vol. 6, No. 3, pp. 415-432, 2019.

[8] Yuvaraj N. and Kumar M.P.: Performance and Surface Evaluation Characteristics on Cryogenic-Assisted Abrasive Water Jet Machining of AISI D2 Steel, in: Kaushik Kumar (Ed.): *Non-Conventional Machining in Modern Manufacturing Systems,* IGI Global, USA, pp. 202-231, 2019.

[9] Yuvaraj, N. and Kumar, M.P.: Multiresponse Optimization of Abrasive Water Jet Cutting Process Parameters Using TOPSIS Approach. Mater Manuf Processes, Vol. 30, No. 7, pp. 882-889, 2015.

[10] Yuvaraj, N. and Kumar, M.P.: Investigation of process parameters influence in abrasive water jet cutting of D2 steel. Mater Manuf Processes, Vol. 32, No. 2, pp. 151-161, 2017.

[11] Chakravarthy, S.P. and Babu, N.R.: A hybrid approach for selection of optimal process parameters in abrasive water jet cutting. Proc Inst Mech Eng Part B: J Eng Manuf, Vol. 214, No. 9, pp. 781–91, 2000.

[12] Jegaraj, J.J. and Babu, N.R.: A soft computing approach for controlling the quality of cut with abrasive waterjet cutting system experiencing orifice and focusing tube wear. J Mater Processes Technol, Vol. 185, No: 1-3, pp. 217–227, 2007.

[13] Srinivasu, D.S. and Babu, N.R.: A neuro-genetic approach for selection of process parameters in abrasive waterjet cutting considering variation in diameter of focusing nozzle. Appl Soft Comput, Vol. 8, No. 1, pp. 809–819, 2008.

[14] Caydas, U. and Hascalik, A.: A study of surface roughness in abrasive waterjet machining process using artificial neural networks and regression analysis method. J Mater Process Technol, Vol. 202, No. 1-3, pp. 574–582, 2008.

[15] Azmir, M.A. and Ahsan, A.K.: A study of abrasive water jet machining process on glass/ epoxy composite laminate. J Mater Process Technol, Vol. 209, No. 20, pp. 6168–73, 2009.

[16] Zain, A.M., Haron, H. and Sharif, S. Optimization of process parameters in the abrasive waterjet machining using integrated SA–GA. Appl Soft Comput, Vol. 11, No. 8, pp. 5350–9, 2011.

[17] Aich, U., Banerjee, S., Bandyopadhyay, A. and Das, P.K.: Multi-objective optimisation of abrasive water jet machining responses by simulated annealing and particle swarm. Int J Mechatron Manuf Syst, Vol. 7, No. 1, pp.38–59, 2014.

[18] Iqbal, A., Dar, N.U. and Hussain, G.: Optimization of abrasive water jet cutting of ductile materials. J Wuhan Univ Technol-Mater Sci Ed, Vol. 26, No. 1, pp. 88-92, 2011.

[19] Liu D, Huang C, Wang J, Zhu H, Yao P, Liu Z. Modeling and optimization of operating parameters for abrasive waterjet turning alumina ceramics using response surface methodology combined with Box–behnken design. Ceram Int 2014;40(6):7899–908.

[20] Azmir, M.A., Ahsan, A.K., Rahmah, A., Noor, M.M. and Aziz, A.A.: Optimization of abrasive water jet machining process parameters using orthogonal array with grey relational analysis. in: *Regional conference on engineering mathematics, mechanics, manufacturing and architecture*, 2007, pp. 21–30.

[21] Satyanarayana, B. and Srikar, G. Optimization of abrasive water jet machining process parameters using Taguchi Grey relational analysis. Int J Mech Prod Eng Res Dev, Vol. 2, No. 9, pp. 82–87, 2014.

[22] Sharma, V., Chattopadhyaya, S. and Hloch, S.: Multi response optimization of process parameters

based on Taguchi—fuzzy model for coal cutting by water jet technology. Int J Adv Manuf Technol, Vol. 56, No. 9–12, pp. 1019–25, 2011.

[23] Santhanakumar, M., Adalarasan, R. and Rajmohan, M.: Experimental modelling and analysis in abrasive waterjet cutting of ceramic tiles using grey-based response surface methodology. Arabian J Sci Eng, Vol. 40, No. 11, pp. 3299–311, 2015.

[24] Marichamy, S., Ravichandran, M., Stalin, B. and Sridhar Babu, B.: Optimization of Abrasive Water Jet Machining Parameters for α-β brass using Taguchi Methodology. FME Transactions, Vol. 47, pp.116-121, 2019.

[25] Kishore, S.J., Teja, P.C., Eshwariaha, B. and Reddy, K.H. Experimental Control of Kerf Width Taper During Abrasive Water Jet Machining. FME Transactions, Vol. 47, No.3, pp.585-590, 2019.

[26] Olson, D.L.: *Comparison of weights in TOPSIS models*, Mathematical and Computer Modelling 2004, 40, 721–727.

[27] Opricovic, S. and Tzeng, G.H.: Compromise solution by MCDM methods-A comparative analysis of VIKOR and TOPSIS. European Journal of Operational Research, Vol. 156, pp. 445–455, 2004.

[28] Ozcan, T., Celebi, N. and Esnaf, S.: Comparative analysis of multi-criteria decision making methodologies and implementation of a warehouse location selection problem. Expert Systems with Applications, Vol. 38, pp. 9773–9779, 2011.

[29] Figueira, J. and Roy, B.: Determining the weights of criteria in the ELECTRE type methods with a revised Simos' procedure. European Journal of Operational Research, Vol. 139, pp. 317–326, 2002.

[30] Yuvaraj, N., Kumar, M.P.: Study and evaluation of abrasive water jet cutting performance on AA5083-H32 aluminum alloy by varying the jet impingement angles with different abrasive mesh sizes. Int J Mach Sci Tech, Vol. 21, No. 3, pp. 385-415, 2017.

NOMENCLATURE

AAJ	Abrasive aqua jet
CAAAJ	Cryogenic assisted abrasive aqua jet
MRR	Metal removal rate
DOP	Depth of penetration
KW_{avg}	average kerf slot
TR	traverse rate
R_a	Average roughness
KTR	Kerf taper ratio
C_i	Closeness coefficient
r_{ij}	normalized performance matrix values
x_{ij}	value of ith exp. run with jth response.
v_{ij}	Weighted normalized matrix values
w_j	Weighted value
D^+_{ij}	best substitute distance
D^-_{ij}	worst substitute distance
S^+	Positive ideal result
S^-	Negative ideal result
P	Aqua jet pressure
GS	Abrasive grit size
IA	Jet impact angle
DOF	Degrees of freedom

ЕКСПЕРИМЕНТАЛНО ИСТРАЖИВАЊЕ КРИОГЕНО ПОТПОМОГНУТЕ ОБРАДЕ ЧЕЛИКА ЗА КАЛУПЕ АБРАЗИВНИМ ВОДЕНИМ МЛАЗОМ

Д.К. Супан, Р. Тилалговиндан, Ј. Натараџан

Рад приказује процес истраживања параметарске оптимизације поступка обраде абразивним воденим млазом (ААЈ) и криогено потпомогнуте обраде абразивним воденим млазом (СААAJ) који се користе за резање AISI D2 челика применом више-циљног TOPSIS приступа. Разматрани су следећи улазни параметри: притисак воденог млаза, величина абразивних зрна и угао удара млаза. Дубина продирања, брзина скидања материјала, однос конусног зареза и просечна храпавост су узете за карактеристике перформанси. Резултати показују да СААAJ поступак има боље карактеристике перформанси у односу на ААЈ поступак. Машинска обрада ААЈ поступком при нагибном ударном углу млаза утиче на излазни одзив, што се види на основу селекције оптималних параметара. Утицај променљивих одређен је анализом варијансе. Укупне перформансе оба поступка су побољшане применом оптималних променљивих поступка обраде коришћењем TOPSIS методе.