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Optimisation of Process Parameters of Abrasive Waterjet Machining Process for Carbidic Austempered Ductile Iron [Cadi]

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Abstract - **Abrasive waterjet cutting is one of the non-traditional cutting processes, which has proven being capable of and widely used to cut the wide range of hard-to-cut materials. This paper investigates the effect of process parameters of abrasive waterjet cutting on Material Removal Rate (MRR) & Surface Roughness (Ra), as these performance measures are important, and play an important role in determining the quality of engineering components. Taguchi's design of experiments, the signal-to-noise (S/N) ratio, and analysis of variance (ANOVA) was carried out in order to invesigate and analyze the effects of the input parameters on material removal rate and surface roughness for cutting the 'carbidic austempered ductile iron' (CADI), using abrasive waterjet cutting process. L9 Taguchi orthogonal array (OA) was used. In order to achieve the maximum MRR and minimum surface roughness (Ra), three input parameters with three levels, was applied to determine the optimal combination of parameter levels. The input process parameters considered in the study included traverse speed, abrasive flow rate and standoff distance. By varying these parameters, the experiments were conducted, and effect of these parameters on responses was investigated and optimum values of process patameters were determined successfully.**

Keywords: Abrasive waterjet cutting, Carbidic austempered ductile iron, taguchi method.

1. INTRODUCTION

Now-a-days, manufacturing industry became more time conscious, with regard to the global economy. The need of speedy prototyping and tiny production batches has been increased, in the modern industries. These trends put ahead the need of using new and advanced production processes, for rapidly dealing out the raw materials to convert into usable goods; with minimum possible tooling time. Water Jet technology was found its intial applications to cut soft material, near around 1970s or so. Use of 'abrasive jets' extended the concept about ten years later. The concept of material cutting using 'abrasive waterjets' in industry was started in the late 1980's. Abrasive Waterjet Cutting [AWJC] has its distinct advantages, over other non-traditional machining processes, such as no thermal distortion, high machining versatility, minimum stresses on the work piece, high flexibility and small cutting forces, and has been established it as an effective technology for processing various engineering materials. It is superior to a lot of other cutting techniques used in processing of the wider range of materials and has found widespread applications in industry. It is also a cost effective and environmentally friendly technique that can be adopted for processing number of engineering materials particularly difficult-to-cut materials [1-6].

1.1 Working Principle Of Awjm

The working principle of AWJM is shown in Fig. 1. The high pressure pump is consist of of an intensifier, prime mover, regulator, and an accumulator. Pure water is supplied under pressure to about 200-400MPa (2000-4000bar) and feed to the element called cutting head through high pressure tube. The high pressure water is then passed through a small orifice, to form a very high velocity Waterjet. This Waterjet then enters in to the mixing chamber to get mixed with abrasives particles, through abrasive supplying system and after mixing the abrasives with water, high velocity mixers then strike to the work piece and cut the material. The position and motion of the cutting head is controlled by computerized numerical control (CNC) system [7].

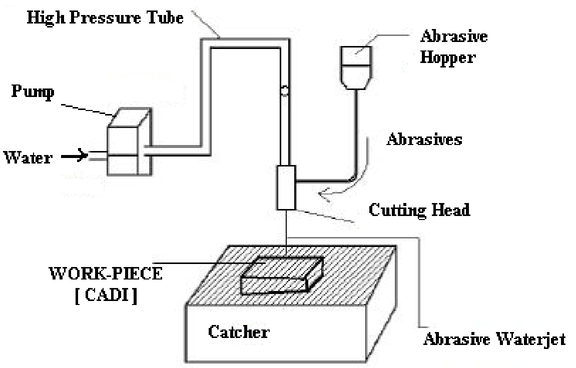

Fig. 1: Schematic of an Abrasive Water Jet Cutting System

2. MATERIALS & METHODS

2.1 Material - Carbidic Austempered Ductile Iron [CADI]

Carbidic Austempered Ductile Iron (CADI) described as a member of ductile cast irons family, with engineered amounts of carbides that are subsequently austempered, to acquire adequate toughness and excellent wear resistance, in it. This Carbidic Austempered Ductile Iron (CADI), containing free carbides in its microstructure, has been purposely designed for applications requiring high levels of abrasion resistance, but still keeping sufficient level impact toughness. By incorporating the carbides in the typical matrix of DI, the Carbidic ductile iron CDI has been developed. Austempering the CDI, lead to a microstructure of carbides distributed in the typical ausferritic matrix, resulting in to CADI. The abrasion resistance of this new material is improved over that of ADI and increases with increasing carbide content. The presence of carbides promotes an increase in the abrasion wear resistance [8-9].

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Chemical Composition of Carbidic Austempered Ductile Iron [CADI] used in experiment by wt%, was C-1.79, Mn-0.54, Cr-2.30, Ni-0.51, Mo-0.014, S-0.013, P-0.016, Si-2.02, Al-0.027, Cu-0.63, Mg-0.054, Ti-0.010. The material used in this experiment was a cast square bar susequnently machined to a size of 15mm X 15mm X 200mm. The material was supposed to cut into pieces of size 15mm using Abrasive waterjet Cutting Process.

2.2 Equipment - Abrasive Waterjet Cutting Machine

The equipment used in the experiment for cutting the samples, was Water Jet Germany cutter. It was equipped with KMT Jetline-50, 550000psi, ultra-high pressure pump. Max. flow rate 3.8l/min. It was also equipped with a gravity-feed type of abrasive hopper, an abrasive feeder system, a pneumatically controlled valve. A work piece table size was 3000 mm x 1500 mm. The Sapphire orifice of 0.35mm internal diameter, was used for transforming the high-pressure water into a focused collimated jet, along with a carbide nozzle of 1.1 mm internal diameter, to form a high velocity abrasive waterjet. The abrasives, Garnet, mesh size 80, round shape, were delivered from a hopper to the mixing chamber, using compressed air and were regulated using a metering disc. The debris of material and the slurry were collected into a catcher tank. The waterjet pressure was kept constant at 46000psi

2.3 Fixture

A fixture was used to hold the workpiece material to cut into the samples of required size, as shown in figure 2. It was consist of base plate, fixture body and top plate. The Fixture body, which consist of rectangular slot, along with under cuts, to hold the work material, was mounted on base plate with the help of allen bolts. The top plate was covering the fixture body and fastened with help of allen bolts. During performing the experiment, the fixture was mounted on machine work-table.

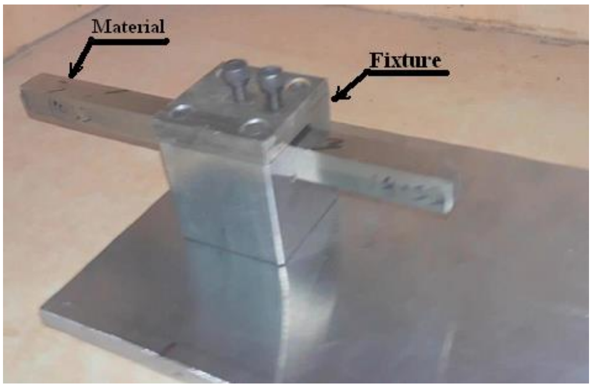

Fig. 2: - Fixture

Fig. 3: - Experimental set-up for AWJ cutting.

3. EXPERIMENTAL WORK

3.1 Taguchi's design of experiments (DOE): -

Taguchi method is a systematic application of design of experiments and analysis, for the purpose of designing and improving product quality. The Taguchi method uses a special Orthogonal Array, to study all the designed factors with a minimum of experiments. Orthogonality means that each factor is independently evaluated and the effect of one factor does not interfere with the estimation of the influence of another factor [10-11]. Table 1 shows the AWJM process parameters investigated at the three experimental levels. In the next step, a matrix was designed with the appropriate OA's for the selected parameters and their levels

3.2 Process Parameters and their Levels

The independently controllable predominant process parameters of AWJM process that influence the output of process are identified as Traverse Speed, Abrasive Flow Rate and Stand-off Distance. The levels of the parameters are deetermined by referring the previous research work in the field of Abrasive Waterjet cutting used to machine hard-to-cut materials, discussing with the AWJM process-expert engineers, available AWJM set-up and several trials, and are listed in Table 2 [3].

Table 1: - Levels of Process Parameters used for experiment

Sr. No.	**Input Parameters**		**Levels**		
	Title	**Abbreviasion**	**1**	**2**	**3**
1	Traverse Speed (mm/min)	**TS**	40	50	60
2	Abrasive Flow Rate (gms/min)	**AFR**	400	500	600
3	Stand-off Distance (mm)	**SOD**	1	2	3

3.3 Measurement of responses

The MRR for each experiment run, was calculated, by calculating the difference of the weight of the workpiece 'before' and 'after' the cutting, and dividing this difference by the cutting time. The electronic weighing balance with

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10mg accuracy was used for doing the weight of the work piece. Cutting time was calculated by considering the Traverse Speed (TS) of the 'cutting head' and width of workpiece i.e. 15.00 mm [12,13].

In abrasive waterjet cutting, the smooth surface is obtained at the region, near the top edge of cut surface and gradually becomes rougher at the bottom edge. The surface roughness of the samples was measured at about 3 mm from the top edge called 'Smooth Cutting Region' (SCR) [3]. MARSURF-M-400 Mobile Surface Measuring Instrument was used for surface roughness measurement.

4. RESULTS AND DISCUSSION

The knowledge of the contribution of individual factors is a key to deciding the nature of the control to be established on a production process. The optimum condition can be investigated by studying the main effects of each of the input parameter. The main effects indicate the general trends of the influence of the factors. Knowing the characteristics, i.e., whether a higher or lower value produces the preferred results, the level of the factors which are expected to produce the best results can be predicted. [14-15].

The experiments were performed according to Taguchi's L9 orthogonal array, at different parameter levels, keeping all other parameters constant. The effect of each parameter, on the response values, viz. Material Removal Rate (MRR) and surface roughness (Ra), were calculated.

Taguchi method for DOE recommends the standard procedure for analysis of the obtained experimental results. The 'MINITAB 17' software , specifically useful for the design of experiment (DOE) applications, has been used for the analysis of this response data.

4.1 Signal-to-Noise ratio

Taguchi method recommends the signal-to-noise (S/N) ratio, which is a performance characteristic, instead of the average value. Optimum conditions were determined using the S/N ratio from experimental results. There are three S/N ratios of common interest for the optimization of static problem, i.e., the higher the better (HB), the lower the better (LB), and the nominal the better (NB). The larger S/N ratio represents to better performance characteristic. The mean S/N ratio at each level for various factors was calculated. Moreover, the optimal level, that is the largest S/N ratio among all the levels of the factors, can be determined [16]. AS the research aims to optimize the process parameters to give higher value of material removal rate (MRR) and smooth surface after processing material (low value of Ra), therefore 'the larger-the-better' is the principle of the *S/N* ratio for the MRR, and 'the smaller-the-better' is the principle of the *S/N* ratio for the Ra.

Figure 3 & 4 shows the main effect plots for S/N ratio of MRR & RA, respectively, at different parameters viz. traverse speed, abrasive flow rate and standoff distance in Abrasive water jet machining of 'carbidic austempered ductile iron' (CADI).

Table 2: - L-9 Orthogonal Array with observations.

Exp No.	TS	AFR	SOD	MRR	S/N Ratio-MRR	Ra [μm]	S/N Ratio-Ra
1	40	400	1	4.453 3	12.97 37	2.331	- 7.3508
2	40	500	2	3.973 3	11.98 31	2.295	- 7.2157
3	40	600	3	4.160 0	12.38 19	1.923	- 5.6796
4	50	400	2	4.533 3	13.12 84	2.758	- 8.8119
5	50	500	3	4.800 0	13.62 48	2.383	- 7.5425
6	50	600	1	4.666 7	13.38 01	2.307	- 7.2610
7	60	400	3	5.160 0	14.25 30	4.130	- 12.319 0
8	60	500	1	5.480 0	14.77 56	3.826	- 11.654 9
9	60	600	2	5.200 0	14.32 01	3.740	- 11.457 4

Table 3: - Response Table for Signal to Noise Ratios for MRR

Level	TS	AFR	SOD
1	12.45	13.45	13.71
2	13.38	13.46	13.14
3	14.45	13.36	13.42
Delta	2.00	0.10	0.57
Rank	1	3	2
Note: - Larger is better for 'MRR'			

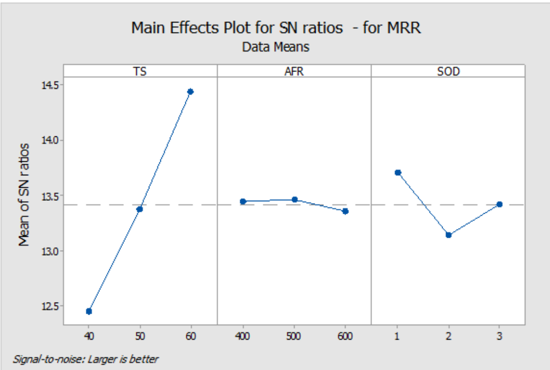

Fig. 4: - Main effects plot for S/N ratio for MRR

Main effects of MRR of each factor for various level conditions are shown in figure 4. According to figure 4 and Table 3, the MRR is mostly influenced by the parameter 'Traverse Speed (TS)'. Standoff Distance (SOD) was observed as the next influencing parameters in AWJC process. Abrasive Flow Rate (AFR) was the least significant parameter for MRR.

Table 4: - Response Table for Signal to Noise Ratios for 'Ra'

Level	TS	AFR	SOD
1	-6.749	-9.494	-8.756
2	-7.872	-8.804	-9.162
3	-11.810	-8.133	-8.514
Delta	5.062	1.361	0.648
Rank	1	2	3
Smaller is better for 'Ra'			

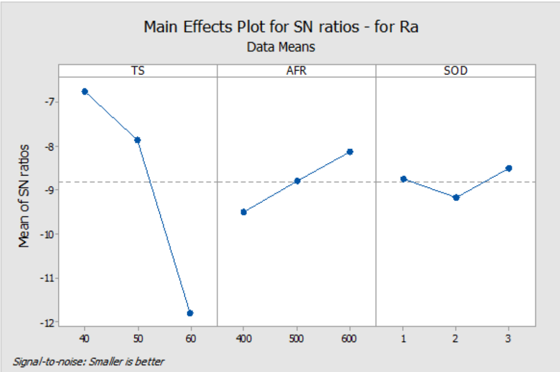

Fig. 5: - Main effects plot for S/N ratio for Ra

Main effects of Ra of each factor for various level conditions are shown in figure 5. According to figure 5, and Table 4, the Ra is mostly influenced by the parameter 'Traverse Speed (TS)'. Another parameters influencing the MRR, were Abrasive Flow Rate (AFR) and Standoff Distance (SOD), respectively. From the figure 5, it can be noticed that an increase in the traverse speed causes an increase in the surface roughness. This may be anticipated as, traverse speed increases, less overlap of machining action occurs and fewer abrasive particles stikes on the target surface, resulting in increased surface roughness [3]. Proper selection of the process parameters, such as increasing the water pressure and reducing the jet traverse speed, minimises the striations formed on the cut surfaces, resulting in smoother surface [17].

4.2 Analysis of variance (ANOVA)

A statistical analysis of variance (ANOVA) was also performed to indicate those process parameters, which are statistically significant; so that the process parameters with optimal combination can be reproduced. In order to validate the methodology, the confirmation experiments is performed using optimal process parameters to verify the predicted results. If the predicted results are confirmed, the suggested optimum working conditions is adopted [18].

ANOVA was carried out to analyse the effect of process parameters on the material removal rate (MRR) & surface roughness (Ra) and to distinguish the most significant parameters in the generation of high MRR and smooth surface.

Table 5: - Analysis of Variance (ANOVA) for MRR

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
TS	2	1.77414	89.26 %	1.77414	0.887072	24.77	0.039
AFR	2	0.00857	0.43 %	0.00857	0.004286	0.12	0.893
SOD	2	0.13325	6.70 %	0.13325	0.066627	1.86	0.350
Error	2	0.07162	3.60 %	0.07162	0.035812		
Total	8	1.98760	100.00%				

The calculations of ANOVA for MRR, are tabulated in Table 5, which shows that, traverse speed (TS) is the most significant parameter in MRR, (89.26%). SOD was found less influence on MRR (6.70%). Abrasive flow rate was the least significant parameter (< 0.5 %).

Table 6: - Analysis of Variance (ANOVA) for Ra

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
TS	2	5.03837	94.33%	5.03837	2.51918	346.89	0.003
AFR	2	0.26182	4.90%	0.26182	0.13091	18.03	0.053
SOD	2	0.02627	0.49%	0.02627	0.01314	1.81	0.356
Error	2	0.01452	0.27%	0.01452	0.00726		
Total	8	5.34099	100.00 %				

The calculations of ANOVA for Ra, are tabulated in Table 6, which shows that, traverse speed (TS) (94.33%) is the most significant paraneter in achieving the better values of Ra, and has p-value almost 0.003. Abrasive flow rate has the little significe on MRR (4.90%). The 'SOD' is the last significant parameter for Ra (<0.5%), in the given experiment.

4.3 Regression analysis

The regression analysis is a statistical modeling and analysis method applied for expressing the relationship between the dependent and independent variables in terms of mathematical model or expression. The statistical analysis measures the degree of correlation between the variables under consideration and the estimation of performance related to the independent variables. Finally the reliability of the regression model is ensured by comparing the data obtained experimentally with the estimated data. In this paper, traverse speed, abrasive mass flow rate and stand off distance are independent variables, and the values of material removal rate and surface roughness are estimated which are the dependent variables [19].

The regression equation of material removal rate (MRR) is

$$MRR = 2.263 + 0.05422\,TS - 0.000200\,AFR - 0.0800\,SOD \quad (1)$$

The regression equation of surface roughness (Ra) is

Ra = -0.38 + 0.0858 TS - 0.00208 AFR - 0.005 SOD (2)

5. CONCLUSION

- In the present study a parametric analysis carried out for material removal rate & surface roughness for the Carbidic Austempered Ductile Iron (CADI) material, using the abrasive waterjet cutting process. The experiments were conducted under various parameters setting, using AWJM process as per Taguchi L9 orthogonal array.
- The responses for material removal rate & surface roughness, were calculated and measured, and the optimum process parameters were investigated.
- Using analysis of variance (ANOVA) method significant process parameter for MRR and surface roughness were determined.
- It was observed that the influence of Traverse speed (89.26%) was the most influencing on MRR followed by SOD (6.70%) & AFR (0.43%).
- For surface roughness (Ra) the influence of traverse speed (94.33%) was more followed by AFR (4.90%) & S.O.D. (0.49%).
- The optimal parameter setting for the material removal rate (MRR) found as TS (60mm/min), AFR (500gms/min), and SOD (1mm).
- The optimal parameter setting for the surface roughness (Ra) found as TS (40mm/min), AFR (600gms/min), and SOD (3mm).

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