ISSN 1330-3651
UDC/UDK 658.562:[621.924.9:669.71-911.48]

TAGUCHI-FUZZY BASED MAPPING OF EDM-MACHINABILITY OF ALUMINIUM FOAM

Joyjeet Ghose, Vinay Sharma, Nitin Kumar, Ajay Krishnamurthy, Surender Kumar, Zlatko Botak

Preliminary notes

Conventional machining of aluminium foams is a difficult task because of the fact that their cells and cell edges are damaged and/or collapsed during the machining processes and thereby their original properties deteriorated. This problem can be overcome to a certain extent by machining this material by Electro Discharge Machining (EDM) process. The present paper deals with identifying the various control parameters responsible for effective machining of aluminium foam. Taguchi-Fuzzy Logic based technique is used for parameter design of performance characteristics to determine optimal machining parameters for maximum Material Removal Rate (MRR) and minimum Tool Wear Rate (TWR) in EDM. Taguchi-fuzzy based mapping of MRR and TWR with productivity revealed that in order to achieve higher productivity while machining aluminium foam, the two parameters, pulse current and pulse-On time are required to be set high in combination with the low setting of duty cycle.

Keywords: *aluminium foam, machinability, EDM, Taguchi technique, fuzzy logic, TWR, MRR, productivity*

Taguchi-fuzzy utemeljeno mapiranje EDM obradivosti aluminijskih pjena

Prethodno priopćenje

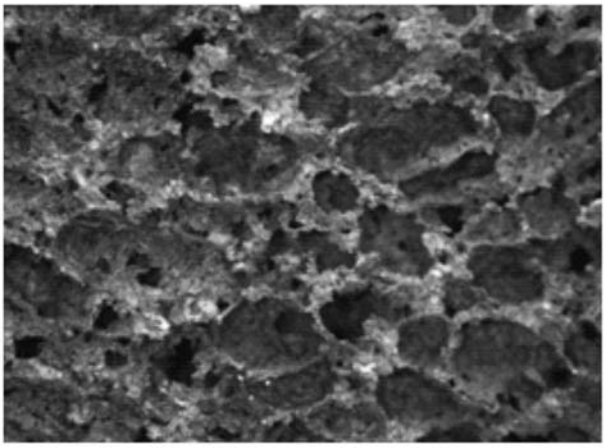
Konvencionalna obrada aluminijskih pjena težak je zadatak s obzirom na činjenicu da su njihove ćelije i rubovi ćelija oštećeni i/ili urušeni tijekom procesa obrade i time pogoršana njihova izvorna svojstva. Taj se problem može prevladati u određenoj mjeri obradom ovog materijala procesom elektro-erozijske obrade (EDM). U ovom članku identificiraju se različiti kontrolni parametri mjerodavni za učinkovitu obradu aluminijske pjene. Tehnika utemeljena na Taguchi-fuzzy logici koristi se za oblikovanje parametara radnih značajki, kako bi se utvrdili optimalni parametri obrade za omjer maksimalnog skidanja materijala (MRR) i omjer minimalnog trošenje alata (TWR) u elektro-erozijskoj obradi. Taguchi-fuzzy utemeljeno mapiranje omjera maksimalnog skidanja materijala i omjera minimalnog trošenja alata s produktivnošću otkrilo je da u cilju postizanja veće produktivnosti pri obradi aluminijskih pjena, dva parametra, "pulse current" i "pulse-on time", moraju biti postavljeni visoko u kombinaciji s nisko postavljenim radnim ciklusom.

Ključne riječi: *aluminijska pjena, obradivost, EDM, Taguchi tehnika, fuzzy logika, TWR, GOP, produktivnost*

1 Introduction

Metal foams are uniform dispersions of a gaseous phase in a solid. Metal foams may be closed cell or open cell; open cell foam is a network of interconnected solid struts whereas closed cell foam is made up of a network of adjacent sealed pores, each sharing their walls with other. Both these types of metal foam have different application suitability. Metal foam offers a unique combination of properties that cannot be achieved by any conventional material at the same time such as high stiffness with ultra-low density, capability to absorb crash energy, and excellent sound absorption properties. Gibson and Ashby (1997) [1] have described cellular solids and their properties in much detail. A metal foam design guide by Ashby et al. (2000) addressed the properties of metallic foams and provided guidelines of how to apply such foams. Of all types of metal foams, aluminium foam is the most widely produced and applied. Of all types of metallic foams, the most popular variety is that made from aluminium alloys.

In spite of existence of such wide varieties of metal foams and such unique combinations of properties, metal foam is still lacking in actual industrial applications. The reasons are high production cost, variability of mechanical properties across sections, cell structure imperfections and difficulty in processing of these materials. The inherent structure of these materials consists of cells/pores, which amplifies the difficulty of machining, welding, etc., of these materials. The common method of machining of metallic foams is by band saw or power saw. Experimental investigations revealed that the machinability of the


(a)

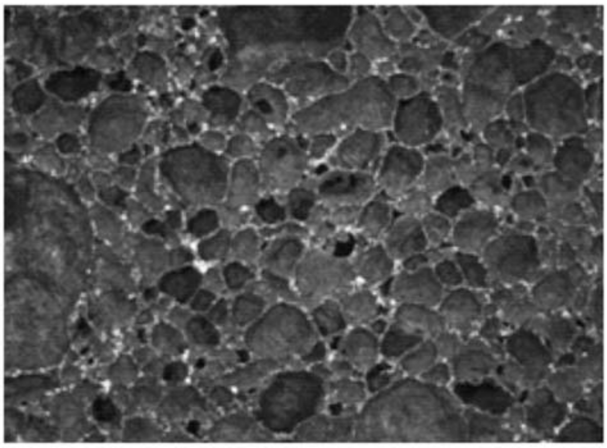

(b)

Figure1 (a) Optical images of specimen surface, machined by band saw; (b) Optical images of specimen surface, machined by EDM.

aluminium foam by these equipments is quite poor as their cells get damaged and/or collapsed during processing either due to the mounting force or the cutting force (Fig. 1a), while machining by advanced [2, 3] technology EDM produces smooth cut with the cell edges almost intact (Fig. 1b).

Investigations are on for finding suitable methods of metal foam machining, one of which is by the use of EDM. Authors have also investigated the machining possibility of the developed closed cell aluminium foam using Wire-EDM. It is found that during machining aluminium foam in Wire-EDM, frequent wire breakages and interruptions in machining took place. This may be due to the presence of uneven pores or larger pores inside the matrix. It is therefore decided to carry out experimental investigations of machining of aluminium foam using EDM. Thus of all the other methods, EDM may prove to be an excellent and versatile means for machining of metallic foams.

In this paper, an attempt has been made to identify the possibility of utilising EDM to machine such materials. The Taguchi-fuzzy based mapping has been performed for identifying the effects of different process parameters of EDM on the productivity i.e. maximum MRR and minimum TWR.

2 Test material

The material under investigation is the closed cell aluminium foam, produced through liquid metallurgy route in the laboratory. Aluminium alloy used for the production of foam is 24345 IS 733 (4 % Cu; 0,5 % Mg; 1 % Si; 0,6 % Mn; 0,7 % Fe; 0,2 % Zn and Ti and rest Al). Tab. 1 summarises the comparison of mechanical properties of aluminium foam produced and those of the aluminium alloy used for foam production.

Table 1 Mechanical properties of aluminium foam and aluminium alloy

Properties	Aluminium foam (density, 0,4 g/cm^3)	Aluminium alloy (density, 2,7 g/cm^3)
E^* / GPa	1,5	69
σ_{pl}^* / MPa	2,5	120

The aluminium alloy is first molten in an electric resistance furnace. At around 750 °C, SiC (5-10 % by weight) and $CaCO_3$ (3-5 % by weight) are added and stirred. The furnace is then switched off. At around 650 °C, TiH_2 (0,5-1,0 % by weight) is added and stirred. The metal matrix is then allowed to cool in the crucible after taking it out of the furnace. SiC particles in the aluminium melt enhance the viscosity and this stabilizes the foaming process. Both $CaCO_3$ and TiH_2 are used as blowing agent. Decomposition of $CaCO_3$ and TiH_2 releases CO_2 and H_2 respectively, which are entrapped, resulting in porosity of the metal matrix.

3 Test material - examle for Taguchi techniques

The design of experiment (DOE) is carried out based on Taguchi techniques. As no initial data are available for machinability of metal foam, a new approach is required. From the results of some initial experiments performed, the following parameters are selected for the EDM, which can make significant contribution towards the machinability of aluminium foam. These parameters are Duty Cycle (ζ), Pulse-On time (*TON*), Gap Voltage (S_v) and Pulse Current (I_p). An L8 orthogonal array is taken for experimental investigation. The input variables considered for analysis and their respective values are summarized in Tab. 2. Based on initial experimental analysis it is found that there are some interactions present between ζ with *TON*, ζ with Sv and TON with S_v. Accordingly the parameters are arranged for L8 Orthogonal array.

Table 2 Values of parameters

Parameter's symbols	Input Parameters	Value	
		Min (1)	Max (2)
a	Duty Cycle, ζ / %	1	32
b	Pulse on time, *TON* / μs	0,25	3000
c	Gap Voltage, S_V / V	1	100
d	Pulse Current, I_P / A	1	50

All the experiments are carried out in CNC controlled EMT 43 Elektra with liquid paraffin as dielectric. The tool used for the experiments is of 10 × 5 cm size, made from thin strip of electrolytic copper sheet (99,96 % pure). The work piece is mounted on the EDM and the depth of cut 14 mm is provided for each experiment. The response variables selected in this study are Material Removal Rate (*MRR*) and Tool Wear Rate (*TWR*). The *MRR* and *TWR* are the machining efficiency of the process and the wear of copper electrode respectively, and are defined as follows:

$$MRR = \frac{\text{mass loss of metal} \times 1000}{\text{density of workpiece} \times \text{machining time}}, \text{ mm}^3/\text{s} \qquad (1)$$

$$TWR = \frac{\text{mass loss of electrode} \times 1000}{\text{density of electrode} \times \text{machining time}}, \text{ mm}^3/\text{s} \qquad (2)$$

The work piece and electrode are weighed before and after each experiment using an electric balance with a resolution of 0,01 mg to determine the value of *MRR* and *TWR*. For each set of values, three experiments are performed in randomised sequence in order to eliminate the influence of systematic errors, as recommended by Taguchi. The S/N ratios are calculated based on "Higher the better" for *MRR*, and "Smaller the better" for *TWR*. The results are summarised in Tab. 3.

The details of the notation used are: *a*: ζ, *b*: *TON*, *ab*:

Table. 3 Taguchi's L8 Orthogonal array for design of experiments and the experimental results

S. No	*a*	*b*	*ab*	*c*	*ac*	*bc*	*d*	*MRR* (S/N)	*TWR* (S/N)
1	1	1	1	1	1	1	1	55,81	164,74
2	1	1	1	2	2	2	2	69,12	142,99
3	1	2	2	1	1	2	2	110,97	101,47
4	1	2	2	2	2	1	1	81,52	151,61
5	2	1	2	1	2	1	2	85,45	137,91
6	2	1	2	2	1	2	1	65,59	158,99
7	2	2	1	1	2	2	1	10	140,51
8	2	2	1	2	1	1	2	53,99	129,53

Table 4 ANOVA summary for *MRR*

(A) Sequence of Variation	(B) Sum of Squares	(C) Degree of Freedom	(D) Mean Square = (B) / (C)	(E) F0 = (D) / Mean square of (e)	(F) F = Value from F table with 0,05 level of confidence	Significance
a	1310,8531	1	1310,8531	35,3676	18,5	Significant
b	47,5391	1	-	-	18,5	
ab	2987,8924	1	2987,8924	80,6151	18,5	Significant
c	7,984	1	-	-	18,5	
ac	202,6728	1	202,6728	5,4682	18,5	
bc	55.6681	1	-	-	18,5	
d	1420,5622	1	1420,5622	38,3276	18,5	Significant
(e) = Cumulative error=Sum of least significant (B) values	111,1912	3	37,063733	1,0000	18,5	

Table 5 ANOVA summary for *MRR*

(A) Sequence of variation	(B) Sum of squares	(C) Degree of freedom	(D) Mean square = (B) / (C)	(E) F0 = (D) / Mean square of (e)	(F) F = Value from F table with 0,05 level of confidence	Significance
a	4,6883	1	-	-	18,5	
b	830,3628	1	830,3628	17,4072	18,5	
ab	96,6133	1	-	-	18,5	
c	185,1927	1	185,1927	3,8822	18,5	
ac	41,8045	1	-	-	18,5	
bc	198,2399	1	198,2399	4,1557	18,5	
d	1350,2742	1	1350,274	28,3064	18,5	Significant
(e) = Cumulative error = Sum of least significant (B) values	143,1061	3	47,70203	1	18,5	

Interaction between ζ and *TON*, *c*: S_v, *ac*: Interaction between ζ and S_v, *bc*: Interaction between *TON* and S_v, *d*: I_p. The analysis of variance (ANOVA) is used to establish statistically significant machining parameters. ANOVA for *MRR* and *TWR* is shown in Tabs. 4 and 5 respectively. From the ANOVA analysis it is clear that parameters *ab*, *d*, and *a* have significant effect on MRR (in descending order of significance) at 95 % confidence level, as *F* value calculated is more than the value of *F* from the table. The parameter d has significant effect on *TWR*.

4 Parametric mapping using fuzzy logic

Fuzzy logic has great capability to capture human commonsense reasoning, decision-making and other aspects of human cognition, Kosko (1997) [4]. According to Klir and Yuan (1998) [5], fuzzy logic involves a fuzzy inference engine and a fuzzification-defuzzification module [6, 7, 8]. A fuzzy-rule based inference engine comprises three basic units: fuzzifier, inference engine and defuzzifier (Fig. 2). The prime function of the system is to establish mapping from inputs to outputs: from cause to effect [9, 10, 11]. However, this mapping mechanism is not built on any precisely defined analytical equation, instead, it is constructed on human knowledge, experience and intuitions often represented in natural languages in the form of if-then rules. It works just like an expert who reasons and infers, by using the knowledge on the inputs and derives solutions as outputs. Several authors have incorporated fuzzy logic for optimizing machining parameters. Lin et al. (2000) [12] demonstrated the effectiveness of using the Taguchi method with fuzzy logic for optimizing the electrical discharge machining process with multiple performance characteristics. Lin and Lin (2005) [13] experimentally validated the use of grey-fuzzy logic approach to optimize the electrical discharge machining process with multiple process responses.

Taguchi's design of experiment is used to find out the influential parameter of EDM machining of aluminium foams. In order to optimize the machining parameters, an output parameter, productivity, is defined. The output membership function, productivity, is defined as the number of products produced in a particular time. The defined productivity has been set a range of 0 to 1. To find the most effective set of parameters and their relative influence on overall productivity, optimization becomes a necessary step. For better productivity, the criterion set is "Higher the better" for *MRR*, and "Smaller the better" for *TWR*. This criterion is incorporated using a set of rules. The optimisation of the parameters (mapping of input and output space) is done using fuzzy logic technique. The desired output is maximum productivity i.e. large volume of material removed with minimum tool wear. In above section separate analysis is carried out on each individual response. This is not a reasonable and valid approach as the optimal factor settings for one response are not necessarily compatible with those of other response. For multiple response problems, it is important to optimize them simultaneously rather than optimizing one response at a time. In the above case if the final solution is left to engineering judgment and experience then it will be more subjective in nature. Because of the above problems, it is better to analyze such case study using S/N ratios and fuzzy-rule based inference system. Instead of leaving it to engineering guesswork, this is a much more structured and rigorous methodology that delivers results that are more convincing. Fuzzy rules are derived from the knowledge and experience. Through inference, the two S/N ratios values will be mapped into a single performance index called Multiple Performance Statistic (MPS) output, upon which the optimum level settings can be identified. In this work the fuzzy logic inference system for this problem is developed using MathWorks™ MATLAB® 7.8.0 (Release 2009a), Fuzzy Logic Toolbox. The input variables for the fuzzy logic inference system are S/N ratios of *MRR* and *TWR*, derived experimentally using Taguchi's technique and the output variable is productivity (Fig. 2).

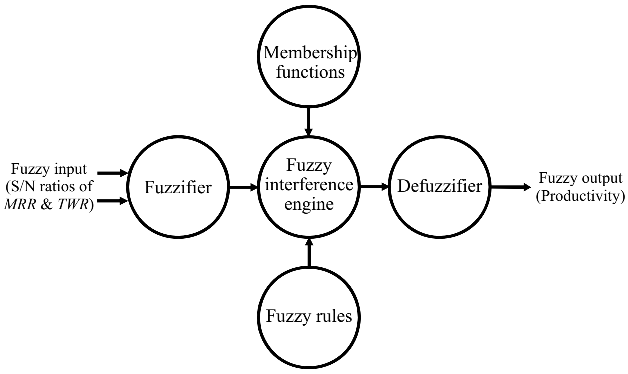


Figure 2 Structure for two inputs and one fuzzy logic output

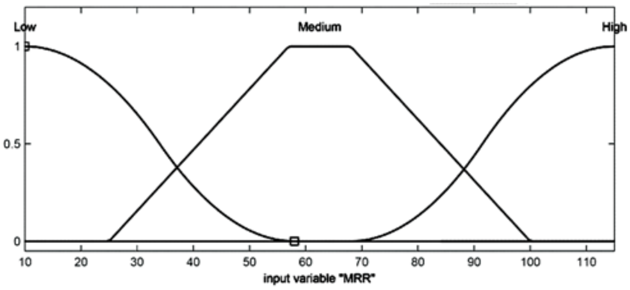


Figure 3 Membership function of *MMR*

The input variables (*MRR* and *TWR*) are represented by membership functions having three levels, namely low, medium and high as shown in Figs. 3 and 4.

The output variable (Productivity) is represented by membership functions having five levels namely low, low-medium, medium, medium-high and high (Fig. 5). The membership function properties are tabulated in Tab. 6.

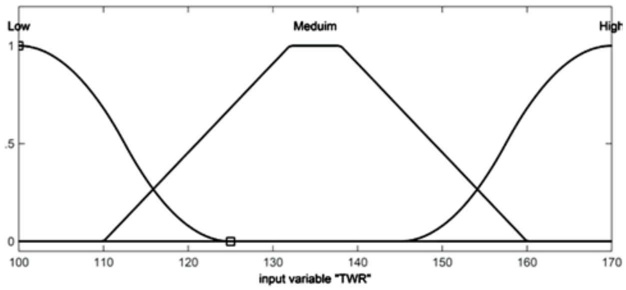


Figure 4 Membership function of *TWR*

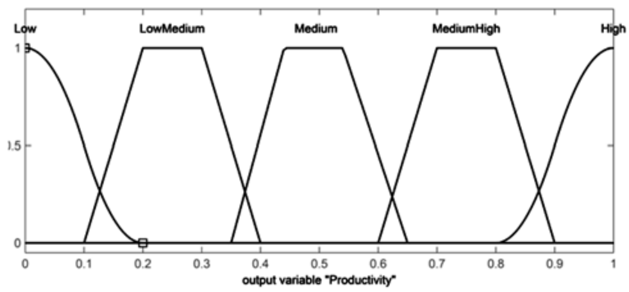


Figure 5 Membership function of productivity

Fuzzification expresses the input variables in the form of fuzzy membership values based on various membership functions. Governing rules in linguistic form are formulated based on observations. The assigned fuzzy rules base consists of if-then control rules with two inputs and one output. The rules used are

– If *MRR* is Low and *TWR* is Low then Productivity is Medium
– If *MRR* is Low and *TWR* is Medium then Productivity is Low Medium
– If *MRR* is Low and *TWR* is High then Productivity is Low
– If *MRR* is Medium and *TWR* is Low then Productivity is Medium High
– If *MRR* is Medium and *TWR* is Medium then Productivity is Medium

Table 6 Membership function properties

Variable	Membership function no.	Levels	Range	Type of Membership function curve
Input variable *MRR* (Range: 10-115)	1	Low	< 58	Asymmetrical polynomial curve open to the left
	2	Medium	25 - 100	Trapezoidal Curve
	3	High	>68	Asymmetrical polynomial curve open to the right
Input variable *TWR* (Range: 100-175)	1	Low	< 125	Asymmetrical polynomial curve open to the left
	2	Medium	132-138	Trapezoidal Curve
	3	High	>170	Asymmetrical polynomial curve open to the right
Output variable Productivity (Range: 0-1)	1	Low	<0,2	Asymmetrical polynomial curve open to the left
	2	Low Medium	0,1-0,4	Trapezoidal Curve
	3	Medium	0,35-0,65	Trapezoidal Curve
	4	Medium High	0,6-0,9	Trapezoidal Curve
	5	High	>0,8	Asymmetrical polynomial curve open to the right

– If *MRR* is Medium and *TWR* is High then Productivity is Low Medium
– If *MRR* is High and *TWR* is Low then Productivity is High
– If *MRR* is High and *TWR* is Medium then Productivity is Medium High
– If *MRR* is High and *TWR* is High then Productivity is Medium.

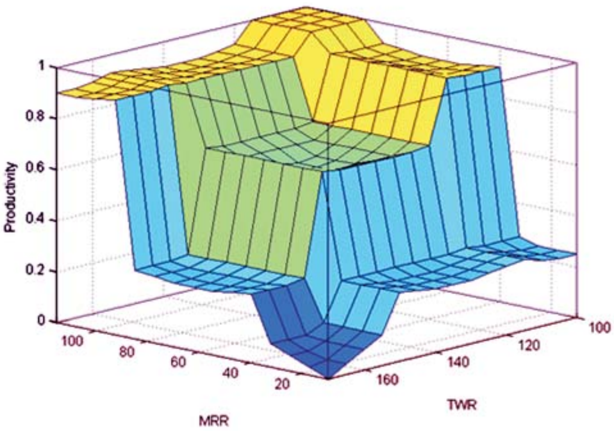


Figure 6 Surface plot of *MRR*, *TWR* and productivity

After defuzzification based on the set of rules assigned the surface obtained for the combinations of input and output is shown in Fig. 6. Productivity is found to be highest when *MRR* ranges between (95, 110) and *TWR* ranges between (100, 115).

The S/N ratios values of *MRR* and *TWR* are used as input in the rule editor of fuzzy inference system and defuzzified values of productivity are obtained correspondingly using the largest value of maximum (LOM) criteria, as shown in Tab. 7.

ANOVA method is used to determine the effect of the machining parameters on the productivity and is shown in Tab. 8. The parameter, which has the maximum value of "mean square of e", will have the maximum influence on the productivity. These values are calculated at 95 % level of confidence. From the ANOVA analysis it is clear that parameters *d*, *a*, *b*, and *ab* have a significant effect on productivity (in descending order of significance) as *F* value calculated is more than the value of *F* from the table. The main effects and their variation between the two levels of the significant parameters on productivity are shown in Fig. 7. The average response curve gives a very good indication about the influence of each parameter on the machinability of foam.

From Fig. 7 it can be concluded that parameters *b*, *ab* and *d* have positive effect on productivity whereas the parameter a has a negative effect on productivity. Therefore as the value of *b*, *ab* and *d* increases, the productivity increases, whereas as the value of *a* increases, productivity decreases. It is also evident from Fig. 7 and Tab. 8 that the parameter *d* has the most significant effect on productivity.

Table 7 Defuzzified values of productivity

S. No	*a*	*b*	*ab*	*c*	*ac*	*bc*	*d*	Productivity
1	1	1	1	1	1	1	1	0,32
2	1	1	1	2	2	2	2	0,52
3	1	2	2	1	1	2	2	1
4	1	2	2	2	2	1	1	0,55
5	2	1	2	1	2	1	2	0,54
6	2	1	2	2	1	2	1	0,35
7	2	2	1	1	2	2	1	0,33
8	2	2	1	2	1	1	2	0,51

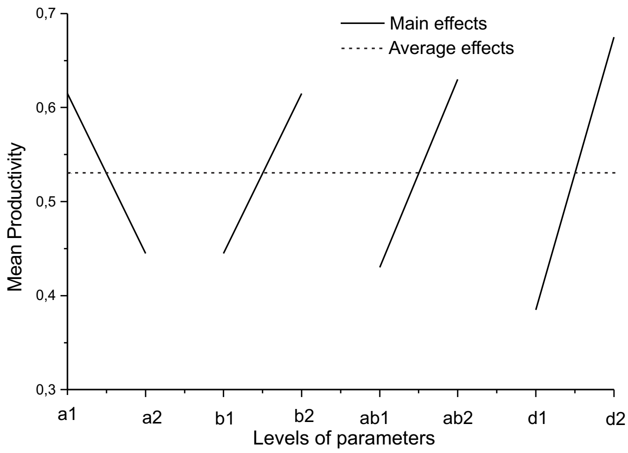


Figure 7 Average responses for productivity

5 Conclusion and remarks

Taguchi-fuzzy based mapping of aluminium foam machining reveals some useful facts. From ANOVA analysis of *MRR* it is found that if interaction between duty cycle - pulse is on time, pulse current and duty cycle are the significant process parameters at 95 % confidence limit. However, for *TWR*, pulse current is the significant parameter at 95 % confidence limit. In order to maximize the productivity not only the *MRR* should be high but also the *TWR* should be low.

Table 8 ANOVA for productivity

(A) Sequence of variation	(B) Sum of squares	(C) Degree of freedom	(D) Mean square = (B) / (C)	(E) *F*0 = (D) / Mean square of e	(F) *F* = Value from F table with 0,05 level of confidence
a	0,05780	1	0,05780	21,14634146	10,1
b	0,05780	1	0,05780	21,14634146	
ab	0,08000	1	0,08000	29,26829268	
c	0,00320	1	0,00320	1,170731707	
ac	0,00180	1	0,00180	0,658536585	
bc	0,00320	1	0,00320	1,170731707	
d	0,13005	1	0,13005	47,57926829	
(e) = Cumulative error = Sum of least significant (B) values	0,0082	3	0,002733333	1	

This is because the low *TWR* will not only reduce the cost of production of a tool but also minimise the tool changing time. Therefore, in order to achieve the higher productivity, fuzzy logic is used to optimise the two output parameters *MRR* and *TWR*. Productivity is the highest when *MRR* ranges between 95 and 110 and *TWR* ranges between 100 and 115. From the Taguchi-fuzzy based mapping it is observed that the parameters pulse current, duty cycle, pulse on time, and interaction between duty cycle - pulse on time are the most significant parameters for achieving the maximum productivity. It can be inferred from the present work that in order to achieve higher productivity while machining aluminium foam using EDM process, two parameters pulse current and pulse on time should be set at high along with low setting of duty cycle.

6 References

[1] Gibson, L. J.; Ashby, M. F. Cellular solids, Cambridge University Press, U.K. 1997.
[2] Valíček, J.; Hloch, S.; Kozak, D. Surface geometric parameters proposal for the advanced control of abrasive waterjet technology. // International Journal of Advanced Manufacturing Technology, 41, 3-4(2009), 323-328.
[3] Valicek, J.; Hloch, S. Using the acoustic sound pressure level for quality prediction of surfaces created by abrasive waterjet. // International Journal of Advanced Manufacturing Technology, 48, 1-4(2010), 193-203.
[4] Kosko, B. Neural network and fuzzy systems – A dynamic approach to machine intelligence. Prentice Hall of India, New Delhi, 1997.
[5] Klir, G. J.; Yuan, B. Fuzzy system and fuzzy logic - Theory and practise, Prentice Hall, Engelwood Cliffs, 1998.
[6] Tozan, H.; Vayvay, Ö. The effects of fuzzy forecasting models on supply chain performance. // In Dimitrov D. P. et al. (eds.) Proceedings of the 9th WSEAS international conference on fuzzy systems - advanced topics on fuzzy systems, Book Series: Artificial Intelligence Series-WSEAS, (2008), 107-112.
[7] Tozan, H.; Vayvay, Ö. Fuzzy Forecasting Applications on Supply Chains // WSEAS Transactions on Systems, 7, (2008), 600-609.
[8] Tozan, H.; Vayvay, Ö. Hybrid grey and ANFIS approach to bullwhip effect in supply chain networks. // WSEAS Transactions on Systems, 8, (2009), 461-470.
[9] Sharma, V. et al. Multi response optimization of process parameters based on Taguchi-fuzzy model for coal cutting by water jet technology. // International Journal of Advanced Manufacturing Technology. DOI: 10.1007/s00170-011-3258-x
[10] Tonkovic, Z. et al. Predicting natural gas consumption by neural networks. // Tehnicki vjesnik-Technical gazette, 16, 3(2009), 51-61.
[11] Galzina, V. et al. Application of fuzzy logic in boiler control. // Tehnicki vjesnik-Technical gazette, 15, 4(2008), 15-21.
[12] Lin, J. L. et al. Optimization of the electrical discharge machining process based on the Taguchi method with fuzzy logics. // Journal of Materials Processing Technology, 102(2000), 48-55.
[13] Lin, J. L.; Lin, C. L. The use of grey-fuzzy logic for the optimization of the manufacturing process. // Journal of Materials Processing Technology, 160 (2005), 9-14.

Authors' addresses:

Joyjeet Ghose
Assistant Professor
Dept. of Production Engineering
Birla Institute of Technology
Mesra, Ranchi, India, 835215
Tel: +919431927425, +916512275044
Fax: +916512275401
Email: joyjeetghose@gmail.com

Vinay Sharma
Associate Professor
Dept. of Production Engineering
Birla Institute of Technology
Mesra, Ranchi, India, 835215
Mobile:+919431382632
Email: vinay@bitmesra.ac.in

Ajay Krishnamurthy
Mechanical Engineering Department
Rensselaer Polytechnic Institute
110th, 8th Street, Troy, New York – 12180, USA
Email: krisha6@rpi.edu

Nitin Kumar
Powertrain Development and Testing
Research and Development Wing
Maruti Suzuki India Ltd.
Gurgaon, India
Email: nitinkara04@gmail.com

Surender Kumar
Department of Mechanical Engineering
G. L. A. Institute of Technology & Management
Mathura, U. P., India, 281406
Email: Kr.surender@gmail.com

Zlatko Botak
Veleučilište u Varaždinu
J. Križanića 33/6
42000 Varaždin, Croatia
E-mail: zlatko.botak@velv.hr