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
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>
<thead>
<tr>
<th>Properties</th>
<th>Aluminium foam (density, 0.4 g/cm³)</th>
<th>Aluminium alloy (density, 2.7 g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E’/GPa</td>
<td>1.5</td>
<td>69</td>
</tr>
<tr>
<td>σs / MPa</td>
<td>2.5</td>
<td>120</td>
</tr>
</tbody>
</table>

The aluminium alloy is first molten in an electric resistance furnace. At around 750 °C, SiC (5-10 % by weight) and CaCO3 (3-5 % by weight) are added and stirred. The furnace is then switched off. At around 650 °C, TiH₂ (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 CaCO3 and TiH₂ are used as blowing agent. Decomposition of CaCO3 and TiH₂ releases CO₂ and H₂ respectively, which are entrapped, resulting in porosity of the metal matrix.

3 Test material - example 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 (Sv) and Pulse Current (Ip). 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 Sv. Accordingly the parameters are arranged for L₈ Orthogonal array.

<table>
<thead>
<tr>
<th>Parameter’s symbols</th>
<th>Input Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Duty Cycle, ζ/ %</td>
<td>1</td>
</tr>
<tr>
<td>b</td>
<td>Pulse on time, TON/ μs</td>
<td>0.25</td>
</tr>
<tr>
<td>c</td>
<td>Gap Voltage, Sv/ V</td>
<td>1</td>
</tr>
<tr>
<td>d</td>
<td>Pulse current, Ip/ A</td>
<td>1</td>
</tr>
</tbody>
</table>

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:

\[ MRR = \frac{\text{mass loss of metal}}{\text{density of workpiece} \times \text{machining time}}, \text{mm³/s} \]  
\[ TWR = \frac{\text{mass loss of electrode}}{\text{density of electrode} \times \text{machining time}}, \text{mm³/s} \]

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:
Interaction between $\zeta$ and $TON$, $c$: $S_{ac}$; $ac$: Interaction between $\zeta$ and $S_{ac}$; $bc$: Interaction between $TON$ and $S_{ac}$; $d$: $I_r$.

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 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 engineering judgment and experience then it will be more time. In the above case if the final solution is left to simultaneously rather than optimizing one response at a time. 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-

### Table 4 ANOVA summary for $MRR$

<table>
<thead>
<tr>
<th>(A)</th>
<th>(B) Sum of Squares</th>
<th>(C) Degree of Freedom</th>
<th>(D) Mean square = (B) / (C)</th>
<th>(E) $F_0$ = (D) / Mean square of (e)</th>
<th>(F) $F_0$ = Value from $F$ table with 0.05 level of confidence</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>1310.8531</td>
<td>1</td>
<td>1310.8531</td>
<td>35.3676</td>
<td>18.5</td>
<td>Significant</td>
</tr>
<tr>
<td>$b$</td>
<td>47.5391</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>18.5</td>
<td>Significant</td>
</tr>
<tr>
<td>$ab$</td>
<td>2987.8924</td>
<td>1</td>
<td>2987.8924</td>
<td>80.6151</td>
<td>18.5</td>
<td>Significant</td>
</tr>
<tr>
<td>$c$</td>
<td>7.984</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>18.5</td>
<td></td>
</tr>
<tr>
<td>$ac$</td>
<td>202.6728</td>
<td>1</td>
<td>202.6728</td>
<td>5.4682</td>
<td>18.5</td>
<td></td>
</tr>
<tr>
<td>$bc$</td>
<td>55.6681</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>18.5</td>
<td></td>
</tr>
<tr>
<td>$d$</td>
<td>1420.5622</td>
<td>1</td>
<td>1420.5622</td>
<td>38.3276</td>
<td>18.5</td>
<td>Significant</td>
</tr>
</tbody>
</table>

(e) = Cumulative error = Sum of least significant (B) values

<table>
<thead>
<tr>
<th>(A)</th>
<th>(B) Sum of squares</th>
<th>(C) Degree of freedom</th>
<th>(D) Mean square = (B) / (C)</th>
<th>(E) $F_0$ = (D) / Mean square of (e)</th>
<th>(F) $F_0$ = Value from $F$ table with 0.05 level of confidence</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>4,6883</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>18.5</td>
<td></td>
</tr>
<tr>
<td>$b$</td>
<td>830.3628</td>
<td>1</td>
<td>830.3628</td>
<td>17.4072</td>
<td>18.5</td>
<td></td>
</tr>
<tr>
<td>$ab$</td>
<td>96.6133</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>18.5</td>
<td></td>
</tr>
<tr>
<td>$c$</td>
<td>185.1927</td>
<td>1</td>
<td>185.1927</td>
<td>3.8822</td>
<td>18.5</td>
<td></td>
</tr>
<tr>
<td>$ac$</td>
<td>41.8045</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>18.5</td>
<td></td>
</tr>
<tr>
<td>$bc$</td>
<td>198.2399</td>
<td>1</td>
<td>198.2399</td>
<td>4.1557</td>
<td>18.5</td>
<td></td>
</tr>
<tr>
<td>$d$</td>
<td>1350.2742</td>
<td>1</td>
<td>1350.2742</td>
<td>28.3064</td>
<td>18.5</td>
<td>Significant</td>
</tr>
</tbody>
</table>

(e) = Cumulative error = Sum of least significant (B) values

Table 4 ANOVA summary for $MRR$

Table 5 ANOVA summary for $MRR$

<table>
<thead>
<tr>
<th>(A)</th>
<th>(B) Sum of squares</th>
<th>(C) Degree of freedom</th>
<th>(D) Mean square = (B) / (C)</th>
<th>(E) $F_0$ = (D) / Mean square of (e)</th>
<th>(F) $F_0$ = Value from $F$ table with 0.05 level of confidence</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>111,1912</td>
<td>3</td>
<td>37,063733</td>
<td>1,0000</td>
<td>18.5</td>
<td></td>
</tr>
<tr>
<td>$b$</td>
<td>143,1061</td>
<td>3</td>
<td>47,70203</td>
<td>1</td>
<td>18.5</td>
<td></td>
</tr>
</tbody>
</table>
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).

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.

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
- If MRR is Medium and TWR is Medium then Productivity is Medium High
- If MRR is Medium and TWR is Medium then Productivity is Medium

<table>
<thead>
<tr>
<th>Variable</th>
<th>Membership function no.</th>
<th>Levels</th>
<th>Range</th>
<th>Type of Membership function curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input variable MRR</td>
<td>1</td>
<td>Low</td>
<td>&lt; 58</td>
<td>Asymmetrical polynomial curve open to the left</td>
</tr>
<tr>
<td>(Range: 10-115)</td>
<td>2</td>
<td>Medium</td>
<td>25-100</td>
<td>Trapezoidal Curve</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>High</td>
<td>&gt;68</td>
<td>Asymmetrical polynomial curve open to the right</td>
</tr>
<tr>
<td>Input variable TWR</td>
<td>1</td>
<td>Low</td>
<td>&lt; 125</td>
<td>Asymmetrical polynomial curve open to the left</td>
</tr>
<tr>
<td>(Range: 100-175)</td>
<td>2</td>
<td>Medium</td>
<td>132-138</td>
<td>Trapezoidal Curve</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>High</td>
<td>&gt;170</td>
<td>Asymmetrical polynomial curve open to the right</td>
</tr>
<tr>
<td>Output variable Productivity</td>
<td>1</td>
<td>Low</td>
<td>&lt;0.2</td>
<td>Asymmetrical polynomial curve open to the left</td>
</tr>
<tr>
<td>(Range: 0-1)</td>
<td>2</td>
<td>Low Medium</td>
<td>0.1-0.4</td>
<td>Trapezoidal Curve</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Medium</td>
<td>0.35-0.65</td>
<td>Trapezoidal Curve</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Medium High</td>
<td>0.6-0.9</td>
<td>Trapezoidal Curve</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>High</td>
<td>&gt;0.8</td>
<td>Asymmetrical polynomial curve open to the right</td>
</tr>
</tbody>
</table>
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.

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 \( e^2 \)", 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.

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.
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


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