Optimization of Fatigue Life Parameters with Taguchi Method

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Abstract—This study aims to attain best fatigue life parameters (cycle of number) of GFR/epoxy filament wound composites pipe according to ASTM D 2992. Effects of parameters such as filament angle, surface crack depth-ratio and Stress levels to optimum fatigue test parameters were investigated by using Taguchi technique. Experiments were performed by 3 repeat of orthogonal L₉ series in Taguchi experiment design and signal-noise rate (S/N) was detected. According to experimental results, a stress level is determined to be the most important factor on fatigue life among three factors.

Keywords—Taguchi method, fatigue life, filament wound,

I. INTRODUCTION

Filament winding method is automated process which allows a thermoset resin-impregnated glass reinforcement to be wrapped around a suitable mandrel. The filament winding machine wraps the mandrel with resin-impregnated strands with the required amount and orientation to build the designed reinforced structure. After that winding process the component is cured under high pressure and temperature. Considerable advantages include precise fiber orientations. Mechanical properties of the filament wound parts do not just depend from composition of component material. In addition, process parameters like winding angle, fiber tension, resin type and curing cycle effects the mechanical properties of filament wound parts. Taguchi method was used for optimization of these parameters, helps in optimization process and determines highest effective parameters in test and manufacturing process [1-3].

Dobrzanski et al. studied the thermoplastic composite rings which were manufactured in the thermoplastic filament winding process at selected conditions. Taguchi approach was used to design varying fibers temperature, winding speed, number of layers and roving. Dobrzanski et al. reduced experimental parameters and determined effective parameters by using Taguchi method [3]. Mahapatra et al. developed the polyester composites reinforced three different weight fractions of woven E-glass fiber. For determining the effect of various operational parameters on erosive wear properties of these specimens Taguchi’s orthogonal arrays were used and In an interacting environment erosion experiments and optimum parameters defined [4]. Sahin studied to develop the weight loss model of the aluminum alloy composites with 10wt. %SiC particles by molten metal mixing in terms of grain size, reinforcement size, applied load and sliding distance using the Taguchi method. Sahin determined the optimal parameters with Taguch’s orthogonal array, signal-to-ratio [5]. Yang and Tang used Taguchi method to obtain optimum cutting parameters in machining AISI 1045 steel with cementite carbide cutting tools. They found that cutting speed and feed rate are important among cutting parameters affecting surface roughness as a result of they experiments and analysis [6]. Kamyabi-Gol works the synthesis of of NiO/SiO₂ nanocomposites fabricated by embedding nickel oxide particles, obtained from hex hydrated nickel nitrate (Ni(NO₃)₂·6H₂O), in a silica matrix, through sol–gel method. Because of the fact that the various factors, e.g. PH, EtOH/TEOS/H₂O ratio, Si/Ni ratio, etc., influencing the gelation time of the solutions, they used Taguchi robust design method of system optimization to determine the percent of contribution (%ρ) of each factor [7].

II. EXPERIMENTAL PROCEDURE

Vetrotex E-glass fiber with 1200 Tex (GRP) and 17 μm diameter is used as reinforcement and Ciba Geigy Bisphenol-A Epoxy CY225 resin system is used as matrix. Mechanical properties of composites (matrix and reinforcement are given in Table 1. The filament wound pipes are produced at the filament winding facilities of Izoreel Composite Insulating Materials Ltd., Izmir, Turkey. The wet winding method used for the production of the composite pipes with ±45°, ±55°, ±75° lay-up. The geometry of composite specimen are shown in Figure 1. Six layer of reinforcement thickness 2.15 mm [8-10].

Fatigue test were performed by using a 250 bar PLC controlled servo-hydraulic testing machine. Open ended internal pressure test apparatus are given in Figure 2. According to ASTM D2992 standart, the fatigue tests were carried out under cycling the internal hydrostatic pressure at 0.42 Hz frequency, 30%, 40% and 50% stress levels and R=0.05 stress ratio [10].
Figure: 1 Geometry of specimen [8].

Table 1. Mechanical properties of fiber and resin [10].

<table>
<thead>
<tr>
<th>Materials</th>
<th>$E$ (GPa)</th>
<th>$\sigma_{TS}$ (MPa)</th>
<th>$\rho$ (gr/cm$^3$)</th>
<th>$\varepsilon_t$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy resin</td>
<td>3.4</td>
<td>50-60</td>
<td>1.2</td>
<td>6-7</td>
</tr>
<tr>
<td>E-glass</td>
<td>73</td>
<td>2400</td>
<td>2.6</td>
<td>4-5</td>
</tr>
</tbody>
</table>

Table 2: GRP filament fatigue life parameters [10]

<table>
<thead>
<tr>
<th>Level</th>
<th>Filament Angle ($^\circ$)</th>
<th>surface crack depth-ratio (a/t)</th>
<th>Stress levels ($\sigma_{static}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>45</td>
<td>0.25</td>
<td>0.3</td>
</tr>
<tr>
<td>2</td>
<td>55</td>
<td>0.38</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>75</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

A. Experiment Design with Taguchi Method

Experimental design with Taguchi method is a simple, effective and systematic approach to provide good quality and low cost in manufacturing. Conventional experimental design methods are complicated and they are hard to be used. At the same time these conventional experimental design methods increase experiment quantity with the increasing parameters in manufacturing. This situation increases cost of experiment design and time consumption. With experimental design by Taguchi method, experiment quantity reduced with an orthogonal array and machining conditions are optimized to obtain better quality. In Taguchi method, variation (deviation) between experimental results and desired results are defined as loss function. This loss function is converted to S/N noise rate [11]. This signal noise rate defined in three levels as; the smaller-the better, the larger-the better and the target is the best [12-14]. Equations of the three levels are given below. Optimum fatigue test conditions according to Taguchi method, obtained by using third equation which is the bigger-the better. By using the smaller-the better equation (3) with MINITAB Release 14 software S/N ratios and level values were calculated. S/N ratios according to mentioned equation results are given in Table 2. “n” is repeat number and $y_i$ is measured variable value in equation (3).

$$10 \log \left[ \frac{y^2}{s^2} \right]$$ the nominal the best situation (1)

$$-10 \log \left[ \frac{1}{n} \sum_{i=1}^{n} \frac{1}{y_i^2} \right]$$ the bigger-the better situation (2)

$$-10 \log \left[ \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right]$$ the smaller-the better (3)

Three level values of which were used in experimental design are given in Table 2.

Table 3: $L_9$ Taguchi experimental design and S/N ratio.

<table>
<thead>
<tr>
<th>Factors</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td></td>
</tr>
</tbody>
</table>

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B. Analysis of Taguchi Design and Results

The very basic criterion for experimental data is signal/noise (S/N) ratio. To acquire bigger number of cycle values according to Taguchi method, S/N ratio should have maximum value. Factor level values that were obtained from MINITAB software according to Taguchi design are given in Table 3. From now on, level values of A, B and C factors are selected from Figure 1 and Table 3 to determine optimum cutting conditions of experiments at same circumstances [13]. In this situation, it can be observed from Figure 1 and Table 3 to determine optimum cutting conditions for experiments to be done are 75° for filament angle, 0.25 for surface crack-depth ratio and 0.3 \( \sigma_{\text{static}0\circ} \) for stress level. 

\( \Delta \) Values for every given factor in Table 4, are defining difference between highest S/N ratio and lowest S/N ratio of factor from the highest \( \Delta \) value in Table 3, it is understood that C factor (stress level or loading ratio) has the highest effect.

### Table 4 S/N response table for fatigue life (Number of Cycle).

<table>
<thead>
<tr>
<th>Level</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>72.18</td>
<td>86.52</td>
<td>95.02</td>
</tr>
<tr>
<td>2</td>
<td>82.44</td>
<td>82.90</td>
<td>88.30</td>
</tr>
<tr>
<td>3</td>
<td>90.43</td>
<td>75.63</td>
<td>61.73</td>
</tr>
<tr>
<td>( \Delta )</td>
<td>18.26</td>
<td>10.89</td>
<td>33.29</td>
</tr>
</tbody>
</table>

Figure 3: Number of cycle-surface crack-depth ratio and \( \sigma_{\text{static}0\circ} \) graph.

Figure 4: A, B and C factor levels according to the bigger-the better S/N rate for fatigue life

Figure 5: Normal probability of residuals the cycle number of fatigue life.

Figure 5 shows the normal probability of the residuals of number of cycle (fatigue life).

III. CONCLUSION

In this study, fatigue life analyses were performed according to Taguchi experiment design parameters to optimize ASTM D 2992 tests. Conclusions from present study are given below:

- \( L_\alpha \) Orthogonal array was acquired by using Taguchi method in MINITAB Release 14 software for 3 different levels of fatigue parameters which are filament angles, surface crack-depth ratios and stress levels. By this way, 9 experiments were done. As results of experiments that were performed according to \( L_\alpha \) orthogonal array, S/N rates of N (Number of cycle from S-N curves) were found. Maximum value was searched at S/N rate by using bigger is better S/N rate equation. Maximum S/N rate gives the optimum fatigue parameters. Optimum fatigue parameters which response to maximum S/N rates of A, B and C factors for the highest number of cycle in fatigue test are \( \pm 75^\circ \), surface crack-depth ratios (a/t) 0.25 and stress level 0.3 \( \sigma_{\text{static}0\circ} \), in other words 3, 1, 1 array.

- Factor C (Stress levels) among fatigue test parameters showed the highest effect to results.

- The optimum fatigue test parameters determined by decreasing fatigue test numbers with Taguchi experimental design. Therefore costs of test and production to obtain optimum running condition of filament pipes were reduced. End of analyses, it is determined that in effective parameters shouldn’t be used in experimental works and productions.

REFERENCES
