CHAPTER 4

GREY-TAGUCHI ANALYSIS

A large quantum of engineering effort is consumed in conducting experiments to obtain the information required to make decisions. The goal of experimentation in manufacturing process is to devise means to minimize the deviation of quality characteristics realized from their target value. Design of experiment (DOE) is a structured, organized method that is used to determine the relationship between the different factors affecting a process and its output. DOE methods have been used extensively in industry for process improvement and optimization purposes. Typically, process settings and parameters are optimized by analyzing the process response obtained from designed experiments, carried out on the actual manufacturing process (Montgomery 1997).

In the context of the present work, wide range of cryogenic treatment parameters have been used by the researchers for different materials and reported (Baldissera and Delprete 2008) that each new material has to be treated at different temperatures, different soaking time and cooling/heating rates, in order to achieve the optimum characteristics. The different values (levels) of cryogenic treatment parameters showed various degrees of enhancement on the durability characteristics of materials. Grey-Taguchi optimization is used in this study to obtain maximum enhancement in the durability of the valve by way of optimizing the critical mechanical properties (Wear resistance, hardness and tensile strength) of valve steels (En 52 and 21-4N) through the cryogenic treatment.
4.1 TAGUCHI METHOD

Statistical quality improvement techniques, such as design of experiments, form an essential part of the search for improved product performance. The statistical approach to the design of experiments and the analysis of variance (ANOVA) technique was developed by R.A. Fisher in the early 1920s at the Rothamsted Agricultural Field Research Station in London. Fisher and his coworker Frank Yates were the primary contributors to the early literature on the design and analysis of experiments.

Fisher’s methods of DOE were a fundamental breakthrough from the old and cumbersome scientific tradition of varying one variable at a time. The technique provides a very powerful and economical method to determine significant factors and factor interactions that affect variability of a process outcome. Factor interaction refers to the effect of the relative levels of individual factors on the quality response of the process. In the present work cooling rate, soaking temperature, soaking time, tempering/aging temperature are the 4 factors. 3 levels are considered for each factor. The specific combination of the relative levels of these factors considered for the analysis is called factor interactions. However such interactions between factors were not considered in order to avoid complexity. In spite of that a direct approach would tell that considering 4 factors and each taking values at 3 levels would lead to $3^4 = 81$ experimental conditions to be considered for the optimization study. This becomes quite cumbersome as the property enhancement analysis also adds up to the treatment process for each experimental condition in deciding the optimal combination of treatment parameters. However the Taguchi technique helps to reduce the number of experimental conditions to be considered for optimization by identifying the combinations that truly influence the process. The classical Taguchi technique to the design of experiments was developed in the late 1980s when Genichi Taguchi
developed his own form of the statistical design of experiments which is a continuation of Fisher’s methods.

Taguchi’s approach to DOE was developed in the 1950s by Taguchi, an engineering guru from Japan and more widely recognized as the father of quality engineering. His approach to experimentation was introduced in the USA in the early 1980s. The Taguchi method uses a special design of orthogonal arrays (OA) to study the domain of the entire process parameters with a small number of experiments. An OA is an array or matrix, representing the levels of factors in a series of experiments. For the present study an $L_9(3^4)$ OA shown in Table 4.1 is used. Columns show the levels to be set for a given factor, which varies from experiment to experiment. Each row represents an experiment, showing the settings (level) of every factor for that experiment.

Table 4.1 Experimental design using the $L_9[3^4]$ orthogonal array

<table>
<thead>
<tr>
<th>Expt.</th>
<th>Cooling Rate A</th>
<th>Soaking Temperature B</th>
<th>Soaking Period C</th>
<th>Tempering/Aging Temperature D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
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<td>8</td>
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<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

The ‘L’ notation indicates that the information is based on the Latin square arrangement of factors. A Latin square arrangement is a square matrix arrangement of factors and indicates an orthogonal array information. The
number of rows in the matrix is indicated by 9 and is the number of experiments to be conducted when using this OA. The number of factors considered in the present study is 4 and is the number of columns in the selected OA. The number of levels of each factors considered in the study is 3 and the levels viz 1, 2, 3 are indicated as the array values. It is imperative that the values for the levels are to be judiciously selected by the designer. Thus the $L_9(3^4)$ OA allows 4 factors at 3 different levels to be studied in just 9 experiments instead of 81 experiments. The combination of array values in a row together defines the factor interactions for the specified experiment. The above 9 combinations of factor interaction are representative experiments to study the influence of factors on the process. After deciding on the representative experimental conditions, if the process quality can be assessed by a single measurable property (say wear resistance or hardness etc.) it is a single response problem and the optimization is rather simple. By verifying the considered single response (property) with these 9 experimental conditions the optimization process gets completed. Thus the process ends with the Taguchi analysis itself. But if the process quality is assessed by more than one property it is a multi response problem and the optimization is rather complex because there exists an optimal combination of these responses that results in the best process quality.

The quality of the process in the present case is assessed by three mechanical properties (Yushu Wang (2007)) of the valve steel viz., Tensile strength, Wear resistance and Hardness. It is to be noted that the maximum durability of the valve is attained by an optimal combination of these three properties. But it is not guaranteed that the best (to favour all the three properties together) combination of treatment parameter levels occur in these nine experiments. To ascertain this an optimal combination of the three properties is required. In order to get an optimum combination for maximum durability which may not be a directly measurable property the grey relational
analysis is to be performed with the effects of these nine experiments on the above three properties.

The above procedure is summarized in the following steps. The systematic approach to the use of Taguchi methods for experimental design is given below (Antony et al 2001).

i) Problem recognition and formulation - to establish a good understanding of the problem.

ii) Select quality characteristics - select the appropriate quality characteristic(s) to measure through the experimental study.

iii) Select parameter - determine the important process parameters.

iv) Fix levels - Judiciously fix the number of test levels and their values for the process parameters (two or three levels are commonly used).

v) Select orthogonal array - specify the appropriate OA and assign the process parameters to its columns.

vi) Conduct experiments - according to the chosen OA design.

4.1.1 Signal to Noise Ratio

In Taguchi’s design method the design parameters (factors that can be controlled by designers) and noise factors (factors that cannot be controlled by designers, such as environmental factors) are considered influential on the product quality. The Signal to Noise (S/N) ratio is used in this analysis which takes both the mean and the variability of the experimental result into account. The S/N ratio depends on the quality characteristics of the product/process to be optimized. Usually, there are three categories of the
performance characteristics in the analysis of the S/N ratio; that is, the lower-the-better, the higher-the-better, and the nominal-the-better. The S/N ratio for each response is computed differently based on the category of the performance characteristics and hence regardless of the category the larger S/N ratio corresponds to a better performance characteristic. In the present study the tensile strength and hardness are the higher-the-better performance characteristics, and the wear weight loss is the lower-the-better performance characteristic. The S/N ratio of each response is further transformed into a grey relational grade for the reasons explained in the previous section. The optimal level of a process parameter in this case will be the level with the highest grey relational grade.

4.2 GREY RELATIONAL ANALYSIS

The grey relational analysis is an efficient tool for multi-response analysis. The grey relational analysis owes its origin to the grey system theory. Any system in nature is not white (full of precise information); on the other hand, it is not black (complete lack of information) either; it is mostly grey (a mixture of black and white). The incompleteness of information is the basic characteristic and it serves as the fundamental starting point of the investigation of the grey system. Incomplete information follows from the limited availability of data and the central problem of the grey system theory is to seek only the intrinsic structure of the system, given such limitation of data. The main objective of the grey system theory is to supply information so that one can whiten the greyness (Sahoo and Pal 2007).

In the grey relational analysis, the first step is to perform the grey relational grade generation in which the results of the wear, hardness and tensile test are normalized in the range between 0 and 1. Then, the second step is to calculate the grey relational coefficient based on standard expressions (Noorul Haq 2008) from the normalized data to represent the correlation
between the desired and actual experimental data of the three measurable properties. The overall grey relational grade is then computed by averaging the grey relational coefficient corresponding to each performance characteristic. The overall evaluation of the multiple performance characteristics is based on the calculated grey relational grade. As a result, the optimization of the complicated multiple performance characteristics is converted into the optimization of a single grey relational grade. In the present work, the multi-performance characteristics of the cryo-treated valve steels are converted into a single grey relational grade which will give the combined effect of all the responses. The optimal level of the 4 factors is the individual level with the highest grey relational grade. Thus the optimal level for the individual factors will be individually selected from the column of the OA. The experimental procedure adopted for the grey-Taguchi method is shown in Figure 4.1.

Once the optimal level of the DCT parameters is identified, the final phase is to verify the improvement of the performance characteristics (tensile strength, hardness, and wear resistance) by conducting the confirmation experiments using these optimal levels of factors for the cryo-treatment process. Over and above the process optimization, it is prudent to determine the degree of influence of the factors on the process performance. This would enable one to have a fair knowledge on the significance to be attached with each factor while designing a cost effective cycle for a specific application.
This statistical significance of the factors can be evaluated through the analysis of variance (ANOVA). A statistical ANOVA is performed to find the contribution of each factor for attaining the process outcome.