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Application of multi-objective Taguchi method in the optimization of hybrid thermochemical treatment for AISI 316L stainless steel

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Abstract

This study provides an approach to acquire a consistent quality characteristic of AISI 316L stainless steel after hybrid thermochemical treatment in gaseous tube furnaceby assigning combinations of optimum parameters such as gas composition, holding time and treatment temperature. Multi-objective Taguchi Method is used to determine the optimum process parameters and also Analysis of Variance (ANOVA) to discover the contribution of each parameter towards the Multiple S/N Ratio value that represents the quality of the material. In this research, the optimum level of process parameters combination is obtained with the effect of interaction that is consist of 75% NH_3, 5% CH_4 and 20% N_2 gas composition, with a treatment temperature 425^{o}C and a holding time 12 hours. This study sums up that the interaction between treatment temperature and holding time is the most influential parameter (43.71%). The tendency of interaction is followed by holding time (24.11%) and interaction between gas composition and holding time (17.79%).

Keywords*:*Hybrid Thermochemical Treatment; Multi-objective Taguchi Method;Optimization; Stainless Steel AISI 316 L.

1. Introduction

Stainless steel is a type of alloy steel that is resistant to corrosion in various environments. The main alloy element of this type of steel is the chromium (Cr) with the minimum required concentration of 11 wt%. The use of stainless steel has penetrated to almost all aspects of life because it has good corrosion resistance. Starting from household appliances, industrial equipment, food processing, also its application in the medical world.

Stainless steel is an alternative biomaterial that is most often used as an internal fixation or body graft, one of which is AISI 316L stainless steel which is part of the austenitic type. Austenitic stainless steel has a high ductility so that it is easy to form during the fabrication process. Costs incurred are also considered cheaper than other types of stainless steel, but the deficiency of this stainless steel is that it has low hardness and wear resistance due to its austenitic microstructure. In its application as a biomaterial, in addition to requiring corrosion-resistant material, it also requires the characteristics of hard and wear-resistant material because it will experience a lot of friction load. This friction load allows for wear acceleration that can reduce service life.

These events can be anticipated by applying surface treatment methods to improve the resistance properties of the stainless steel surface. One of the surface treatments that can be done is a hybrid thermochemical treatment process. The hybrid thermochemical treatment was chosen to be applied to AISI 316L stainless steel by giving a hard coating on the surface which can increase the hardness and wear resistance of the material. In this case, the treatment is carried out to increase load bearing capacity when the surgical implant component rubs. It is expected that with this treatment, stainless steel will have good quality and in accordance with the desired, especially as an alternative biomaterial in body grafts. In addition, the parameters of the hybrid thermochemical process must also be controlled so that they have optimal and consistent quality characteristics.

The optimal and consistent quality conditions are represented by surface hardness, layer thickness and surface roughness. The quality characteristics are intended to increase usage life in meeting customer satisfaction. In order to be applied and produced commercially, quality characteristics must be consistent so that fluctuations in the quality of production become lower. Therefore, this study uses an experimental design with the Taguchi method to determine the most optimal level setting of the parameters of the hybrid thermochemical process. Through this research, it is expected that a combination of optimal process parameters can be achieved so that it can produce consistent quality for commercial application.

2. Application of Taguchi method in the manufacturing process

To optimize its process parameters, various studies have been carried out in the laboratory by experimental basis in improving the quality characteristics of its resulting products using the hybrid thermochemical treatment [1-6]. The Taguchi method has been used by previous work [7] to optimize injection molding parameters. The interaction between certain factors: melting temperature, injection pressure and press time, were studied to have an effect on the product shrinkage from the injection molding process. The Taguchi method has also been applied to obtain an optimum product characteristic from the condition of turning process parameters [8]. The method was used in optimizing turning conditions to obtain the lowest surface roughness. Another study used the Taguchi method in achieving the optimum lathe facing operation and it proved that the use of this method can produce accurate data with fewer experiments compared to the experimental combinations using full-factorial design [9].

A previous study has applied the Taguchi method to optimize the milling process parameters associated with the lowest surface roughness [10]. It was proven that the Taguchi method is robust enough to obtain optimum quality characteristics and provide information about the contribution of each factor and interaction on the result. Previous work [11] has concluded that the Taguchi analysis used to investigate the effect of sand-casting process parameters on the resultant hardness and impact energy of aluminum alloy casting can produce a comparable result to empirical implementation. The Taguchi method that was used in optimizing the electrochemical machining process parameters have validated the achievement of optimum process parameters [12]. The Taguchi method has also been applied to obtain maximum wear resistance of Deep Cryogenic Treatment (DCT) process parameters [13]. The work concluded that selections of the process parameters using this technique can lead to the 43.8 % improvement in wear resistance of the martensitic stainless steels after treatment. Another study investigated the influence of normal load, sliding speed and texture area density on the friction performance of MoS_2 coatings using the Taguchi analysis [14]. The laboratory characterization confirmed that the tribological properties of the textured MoS_2 coated surface significantly improved after a selection of laser surface texturing parameters suggested by the Taguchi method. The Taguchi method was used in the previous study [15] to optimize water-repellency performance on rough surfaces using nanoscale roughness inherent in metal oxide nanoparticles together with setting parameters of a hydrophobic fluoromethylic copolymer coating. The evidence from this study showed that the method provides time-saving and cost-efficiency correlated to optimum performance of treated surfaces. These all works [10-15] only focused on the optimization of a single quality characteristic. Optimization of multiple quality characteristics has not been widely presented by the previous literatures and therefore this is considered as the benefit of the present study. The work on a multi-objective Taguchi Method has been introduced in the study of spot-welding processes [16]. It found that the developed model can effectively predict optimum process parameters to improve the quality of the welding process. Multi-objective optimization was also performed in the process of punching metal components and the result confirmed the validity of the experimental design in achieving optimum quality characteristics [17]. Simultaneous optimization of three quality characteristics in the assembly process of electronic components using soldering technique was previously studied using the multi objective Taguchi Method [18]. All the above studies [16-18] however ignored the interaction effects between process parameters, whereas the concept of interaction is essential in the manufacturing processes due to overlapping effect between process parameters that commonly occurs in practical applications. In the present study, an experimental design with the Multi-objective Taguchi Method was used to determine the optimum level setting of the hybrid thermochemical treatment parameters based on multiple quality characteristics. The interaction effects of gas composition, treatment temperature and holding time are investigated.

3. Methodology

The Taguchi method in experimental design is used to determine the optimum settings of parameters to minimize the variation of the production quality. Besides it also used to identify the main factors that have the biggest contribution to variation.This method uses fractional factorial experiment design to reduce the number of experiments and hence results in cost reduction and time efficiency. An orthogonal array is also applied to represent the experimental situations.

After the experimental in the laboratory is conducted, the results are then changedinto the Signal-to-Noise (S/N) Ratio based on the selected quality characteristics.The greater the S/N Ratio value, the higher the quality characteristics. Analysis of Variance (ANOVA)is also applied to determine the most significant process parameters that affect statistical quality characteristics.

A sequential diagram showing the application of Taguchi Method for Hybrid thermochemical treatment of AISI 316L stainless steel is depicted in **Fig. 1.** Two levels were selected for the three set parameters consisting of gas compositions, treatment temperature and holding time as shown in **Table 1**. A selection of these process parameters was made on the basis of previous experimental studies on hybrid thermochemical treatment [3-6]. The selection of the orthogonal array is based on Degree of Freedom of standard orthogonal arrays which should be greater than or equal to the total degrees of freedom in this works. The computation of total Degree of Freedom is done using the equation below:

$$DoF = \sum_{i}^{m}(L-1) + \sum_{i}^{n}\{(L_A-1)\ x\ (L_B-1)\} \qquad (1)$$

where L is the number of levels, m is the factors, n is the interactions, L_A is the factor A and $L_B$is the factor B.

In this work, since three factors with two levels and three interaction between factors are observed, the total degrees of freedom are equal to 6. Therefore, $L_8(2^7)$ orthogonal array was chosen in this study with seven degree of freedom. The experimental layout for hybrid thermochemical treatment is presented in **Table 2**.

After the experiments have been conducted, the data is then converted into the S/N Ratio that represents the quality characteristics. Generally, it can be calculated as:

$$\eta = -10log_{10}[\text{Mean Squared Deviation}] \qquad (2)$$

Mean Square Deviation of the target value also known as Quality Loss Function. Quality Loss Function is an estimate of quality loss that is experienced when quality characteristics deviate from the target value.

Quality Loss Value

Quality Loss Value calculations refer to certain quality characteristics, including:
Smaller-the-better:

$$\text{MSD} = \frac{1}{n}\sum_{i=1}^{n} y_i^2 \qquad (3)$$

Nominal-the-best

$$\mathrm{MSD} = \sigma^2 + (\bar{y} - m)^2 \quad (4)$$

Larger-the-better

$$\mathrm{MSD} = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2} \quad (5)$$

where y_i is observed data at *ith* trial, σ is standard deviation, $\bar{y}$ is mean and *m* refers to the target value.

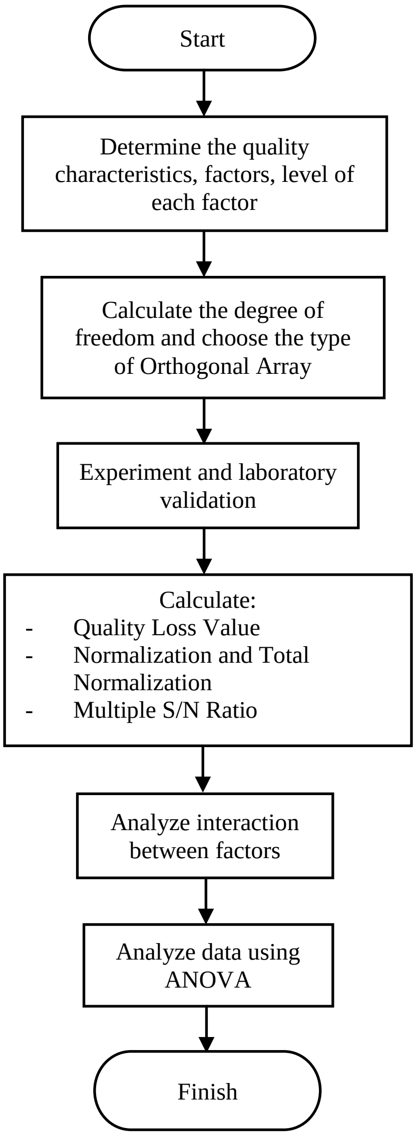


Fig. 1: Experimental Procedures

Normalized Quality Loss Value

Multi-objective optimization that is presented in this study is conducted towards more than one quality characteristics. Normalization calculation is needed to get an equivalent value from quality loss due to the difference of unit of measurement between one characteristic and another that has been developed by several studies [14-16] using the following equation:

$$y_{ij} = \frac{L_{ij}}{L_{i*}} \quad (6)$$

where,

y_{ij} = normalized quality loss value on quality characteristics *i*

L_{ij}= quality loss or MSD from the characteristics of quality *i* in the *jth* trial

$Li*$ = maximum quality loss value on quality characteristics *i*

Table 1:Control factors and levels

Code	Factors	Level 1	Level 2
X_1	Gas composition	75% NH_3 5% CH_4 20% N_2	75% NH_3 15% CH_4 10% N_2
X_2	Treatment temperature	425° C	475° C
X_3	Holding time	6 hours	12 hours

Table 2: Experimental layout $L_8(2^7)$

Experiment	Level Factors						
	X_1	X_2	X_1 X_2	X_3	X_1 X_3	X_2 X_3	e
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

Total Normalized Quality Loss Value

In this step, the weighting factor can be added if there is a quality characteristic which is considered more dominant and affect the overall quality. The equation below is used to calculate the total normalized quality loss value:

$$Y_j = \sum_{i=1}^{k} w_i y_{ij} \quad (7)$$

where,

Yj = total normalized quality loss

wi = weighting factor for quality characteristics *i*

k = number of quality characteristics

Multiple S/N Ratio

In multi-objective optimization, the Multiple S/N Ratio calculation is needed because it’s different from the common S/N Ratio that can’t represent the overall quality characteristics. This requires a separate calculation using the following equation:

$$\eta_j = -10\,log_{10}[Y_j] \quad (8)$$

where,

η_j = multiple S/N ratio

Yj = total normalized quality loss

Analysis of Variance (ANOVA)

Analysis of Variance (ANOVA) in the Taguchi method is used to interpret experimental data by estimating the contribution of each parameters to all response measurements quantitatively.The F-ratio and the percentage contribution are normally used to exhibit the relative significance of factors towards the quality characteristics. If the F-ratio is greater than the F-table, it can be concluded that the parameters or interactions significantly affect the Multiple S/N Ratio value. Nevertheless, if the F-Ratio is smaller than F-Table, the parameters or interactions do not significantly affect the Multiple S/N Ratio.

4. Results and Discussions

Table 3: Experimental results

Run	Layer thickness (μm)						Surface Hardness (VHN)						Surface Roughness (μm)
	1	2	3	4	5	Average	1	2	3	4	5	Average	1
1	0	0	0	0	0	0	210.7	192	187.3	141.2	127.1	171.7	1.5
2	4.26	4.93	4.41	4.67	4.58	4.57	631.8	659.9	715.5	705.2	668.4	676.2	2.55
3	1.04	1.04	1.3	1.3	0.78	1.092	245.5	309.2	305.6	295	284.5	288	1.95
4	4.41	4.15	4.67	3.63	4.15	4.202	1154	1249	1033	847.8	837.7	1024	3.26
5	1.56	2.07	1.56	1.04	1.04	1.454	309.6	281.8	286.5	293.3	282.9	290.8	2.32
6	3.63	3.63	3.11	3.37	4.15	3.578	712.7	629.2	508.8	605.2	626.1	616.4	2.55
7	3.11	3.63	3.37	3.11	3.37	3.318	586.9	493.6	588.9	682	597.7	589.8	2.24
8	15.55	13.48	14	16.59	15.55	15.03	1122	1264	12882	1170	1012	1170	3.38

Table 3 shows the experimental results for the three quality characteristics. From these data, the quality loss values for each quality characteristics are presented in **Table 4** using Eq. (3), (4)and (5).The normalized quality loss values as shown in **Table 5** are calculated using Eq. (6). The total normalized quality loss values are calculated using Eq. (7) and the results are shown in **Table 6**. There is no weighting on the quality characteristics observed in this present studybecause the weighting factors between one variable and another are considered the same due to the level of importance of all quality characteristics are balanced.

Table 4: Quality loss values

Run	Quality Loss Values (dB)		
	Layer thickness (nominal-the-best)	Surface hardness (larger-the-better)	Surface roughness (smaller-the-better)
1	100.0000	0.00003804	2.25
2	31.4171	0.000002654	6.5025
3	79.3998	0.00001232	3.8025
4	33.7655	0.000001029	10.6276
5	73.2203	0.00001187	5.3824
6	41.3908	0.000002728	6.5025
7	44.6964	0.000002968	5.0176
8	26.9506	0.0000007471	11.4244

Table 5: Normalized quality loss values

Run	Normalized Quality Loss Values		
	Layer thickness (nominal-the-best)	Surface hardness (larger-the-better)	Surface roughness (smaller-the-better)
1	1.0000	1.0000	0.1969
2	0.3142	0.0698	0.5692
3	0.7940	0.3239	0.3328
4	0.3377	0.0271	0.9303
5	0.7322	0.3120	0.4711
6	0.4139	0.0717	0.5692
7	0.4470	0.0780	0.4392
8	0.2695	0.0196	1.0000

Table 6: TNQLV and MSNR

Run	Total Normalized Quality Loss Values	Multiple S/N Ratio
1	0.7323	1.3531
2	0.3177	4.9798
3	0.4836	3.1551
4	0.4317	3.6482
5	0.5051	2.9662
6	0.3516	4.5395
7	0.3214	4.9295
8	0.4297	3.6683

The multiple S/N ratios (MSNR) for each experimental run is calculated using Eq. (8) and is presented in **Table 6**. **Table 7** shows the response of MSNR at eachlevel to related factors and interactions. The response value is obtained by calculating the average of the MSNRat each level of each factor. Based on this analysis, the optimum combination was obtained by choosing the highest MSNR value for each parameter i.e. gas composition at level 2 (75% NH_3, 15% CH_4 and 10% N_2), treatment temperature at level 2 (475^{o} C) and holding time at level 2 (12 hours).

Table 7: Multiple S/N response table

Code	Factors	Mean MSNR (dB)	
		Level 1	Level 2
X_1	Gas Composition	3.2841	4.0259
X_2	Treatment temperature	3.4597	3.8503
X_1X_2		3.7327	3.5773
X_3	Holding Time	3.1010	4.2090
X_1X_3		3.1790	4.1309
X_2X_3		2.9090	4.4010

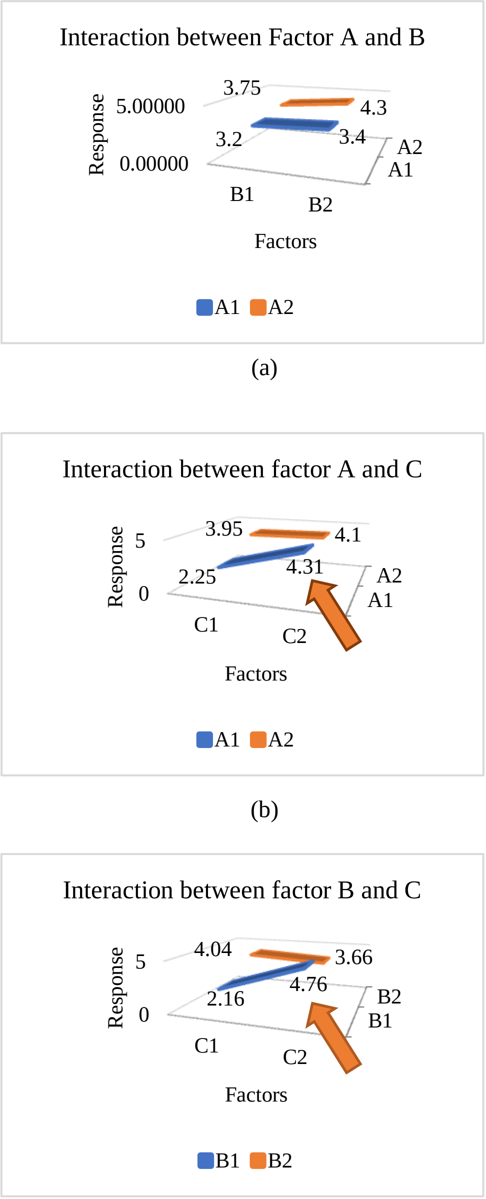
In this study three interactions between factors are included in the orthogonal array. The interactions between factors were analyzed in such a way that when two or more factors act together, they produce different effects when compared to when these factors act individually. Selection to the optimum level of interaction is made by separating the interaction. The interaction of these process parameters in the present study is given in **Fig. 2**. For example, interaction AB has four combinations of factors and levels namely A_1B_1, A_1B_2, A_2B_1 and A_2B_2. In the interaction analysis, the interaction column, column 3, 5 and 6 on the orthogonal array is not used. Only the column containing the individual factors will be used i.e. columns 1, 2 and 4. This is because the average value of the effect of A_1B_1 is not equal to the average value of the influence of AB at level 1.

Evaluation of A_1B_1 interaction based on orthogonal array factor A_1 is found in columns 1 rows 1, 2, 3 and 4 while factor B_1 is in columns 2 rows 1, 2, 5 and 6. By comparing the two factors, the rows that have A_1 and B_1 located in line 1 and 2. The influence of the A_1B_1 interaction is calculated using the average Multiple S/N Ratio value from experiments 1 and 2. The same calculation method is also performed to other interaction between other factors and levels.

Based on the analysis, only the interaction between factors A and B produces graphs with almost parallel lines as shown in **Fig. 2(a).** This interaction between factor A and factor B is ignored due to the weak interaction that occurs between these two factors. **Fig. 2(b)** and **Fig. 2(c)** show intersecting lines representing the existence of interaction between factor A and factor B, and also between factor B and factor C respectively. Based on **Fig. 2(b)** and **Fig. 2(c)** where the highest MSNR is obtained at the combination of A_1C_2 and B_1C_2, thus the optimum level combination of hybrid thermochemical treatment process parameters is A_1, B_1 and C_2. The combination is similar with experiment 2 on the orthogonal array. Accordingly, the quality characteristics produced are layer thickness (4.57 μm), surface hardness (676.12 VHN) and surface roughness (Ra 2.55 μm). **Fig. 3** shows the specimen used in the hybrid thermochemical treatment. The layer morphology and the surface roughness profile are shown in **Fig. 4** and **Fig. 5.**The interaction of BC, factor C

Table 8: Analysis of variance (ANOVA)

Factors and Interactions		DoF	Sum of Squares	Mean Squares	F-Ratio	%
X_1	Gas Composition	1	1.101	1.101	98.422	10.81
X_2	Treatment temperature	1	0.305	0.305	27.290	3.00
X_1X_2		1	0.048	0.048	4.320	0.47
X_3	Holding Time	1	2.455	2.455	219.557	24.11
X_1X_3		1	1.812	1.812	162.066	17.79
X_2X_3		1	4.452	4.452	398.143	43.71
Error		1	0.011	0.011		0.11
Total		7	10.185			100.00



(a)

(b)

(c)

Fig. 2: Interaction between factors

and the interaction of AC are factor and interactions that significantly affect the Multiple S/N Ratio value in this study compared to other factors and interaction. These factor and interactions have F-Ratio values that are greater than F-Tables at a 95% confidence level where the F-Table value is161.448. Interaction BC is the interaction between treatment temperature and holding time which plays the most important role as shown in **Table 8** with the high

Fig. 3: Specimen used in this study

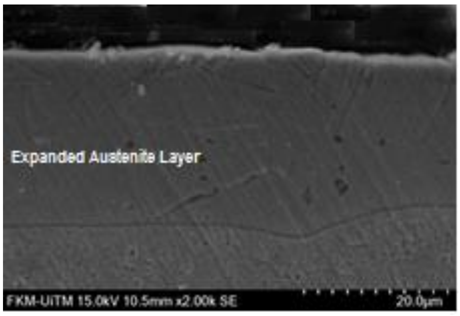
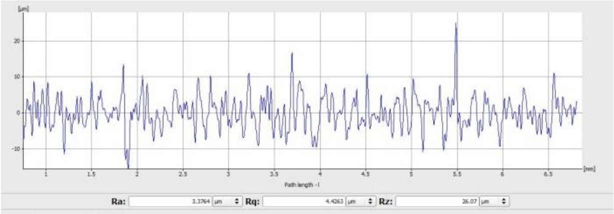


Fig. 4:Layer morphology



Ra: 3.3764 µm Rq: 4.4263 µm Rz: 26.07 µm

Fig. 5: Surface roughness profile

percentage contribution to the Multiple S/N Ratio value which is up to 43.71%. This is followed by holding time, which is 24.11% and the interaction between gas composition and holding time of 17.79 %.

5. Conclusions

- From three interactions that have been observed in this study, there were only two interactions that significantly affected the quality of the produced layers on AISI 316L stainless steel surfaces. These involve the interaction between gas composition and holding time and the interaction between treatment temperature and holding time. The interaction between gas composition and treatment temperature was not found in this study.

- The optimum level combination is achieved by considering the interaction effects of gas composition at level 1 consisting of 75% NH_3, 5% CH_4 and 20% N_2, treatment temperature at level 1 which is set at 425^oC and holding time at level 2 for 12 hours duration.
- The interaction between treatment temperature and holding time is the parameter that contribute the most to the quality of the AISI 316L stainless steel in this study which is 43.71% followed by the holding time (24.11%) and the interaction between the gas composition with the holding time (17.79%).
- Optimum selection of hybrid thermochemical process parameters was obtained using Taguchi Method as a design of heat treatment for surgical implant stainless steel AISI 316L.

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