Robust Parameter Design via Taguchi's Approach and Neural Network

Jeh-Hsin Tsai[1], **Iuan-Yuan Lu**[2]

[1] Ph.D. Candidate, Department of Business Administration
National Sun Yat-Sen University, Kaohsiung, Taiwan, R.O.C.
[2] President of the CSQ & Professor, Department of Business Administration
National Sun Yat-Sen University, Kaohsiung, Taiwan, R.O.C.

ABSTRACT

The parameter design is the most emphasized measure by researchers for a new products development. It is critical for makers to achieve simultaneously in both the time-to-market production and the quality enhancement. However, there are difficulties in practical application, such as (1) complexity and nonlinear relationships co-existed among the system's inputs, outputs and control parameters, (2) interactions occurred among parameters, (3) where the adjustment factors of Taguchi's two-phase optimization procedure cannot be sure to exist in practice, and (4) for some reasons, the data became lost or were never available. For these incomplete data, the Taguchi methods cannot treat them well.

Neural networks have a learning capability of fault tolerance and model free characteristics. These characteristics support the neural networks as a competitive tool in processing multivariable input-output implementation. The successful fields include diagnostics, robotics, scheduling, decision-making, prediction, etc.

This research is a case study of spherical annealing model. In the beginning, an original model is used to pre-fix a model of parameter design. Then neural networks are introduced to achieve another model. Study results showed both of them could perform the highest spherical level of quality.

Key Words: Taguchi methods, Parameter design, Neural networks.

1. Introduction

Taguchi methods includes the system design, robust parameter design and tolerance design, the concept combines engineering technology and statistic methods to define the defect products as a social lost(Phadke, 1989; Phadke and Dehnad 1988). The approaching methods to go well with the qualities control have been developed by the powerful tools of the second order loss function and signal to noise ratio. The variation of product qualities have been considered and covered into the quality research and development activities, while it was not limited to the traditional quality concept, which emphasized that good product has all fitted the specification limit.

Conventionally, engineers apply the Taguchi methods to conduct parameter design in a variety of industrial practices. The Taguchi methods developed a revolutionary concept, and the dramatic success of this methodology lies in combining statistical design of experimental methods with a deep understanding of process problems. The use of Taguchi's approach in manufacturing has been proven very beneficial in process modeling, optimization and control. This approach in process has yielded fairly good empirical models for processes such as Phadke (1989) used the Taguchi methods to study the surface defects and thickness of a wafer in the polysilicon deposition process for a VLSI circuit process.

Taguchi methods, which combine experiment design theory and the quality loss function concept, have been applied to the robust design of products and process and have solved lots of confusing problems of manufacturing. Therefore, the purpose of the present experiments is to use Taguchi methods to investigate the significant factors that influence the spheroidized structure and to build the optimal heat treatment process that will satisfy the customer's requirement.

On the other hand, there has been an increasing amount of neural network application research in the last decade; especially neural networks are often used to identify optimal process setting (Su and Chang, 2003). Neural networks possess the powerful capability of learning nonlinear mappings between the input and output patterns. Therefore, neural networks are also used to evaluate our heat treatment process.

This study aiming at two major purposes of the spherical annealing treatment of bar-in-coil steel, those are;

a. To define the crucial factors for spherical annealing efficiency.
b. To establish the optimal spherical annealing model to fully fit customers' requirement.

2. Spherical annealing

The high ductility of bar-in-coil steel is directly related to the performance of the spheroidized structure. The good ductility of spheroidized structure is extremely important for low- and medium-carbon steels that are cold formed, and the low hardness of spheroidized structure is important for high-carbon steels that undergo extensive maching prior to final hardening.

Spheroidized structures are the most stable structures found in steels and will form in any prior structure heated at temperatures high enough and times long enough to permit the diffusion-dependent development of the spherical carbide particles. As a result, there are many different heat treatment approaches for producing spheroidized structure.

Spheroidized structures are stable because the ferrite is generally strain-free and because the spherical shape of the cementite particles is one of minimum interfacial area per unit volume of particle. Lamellar cementite particles, as present in pearlite, have a very large interfacial area per unit volume of particle and therefore high interfacial energy. In order to reduce the interfacial energy, cementite lamellae or plates break up into smaller particles assume spherical shapes.

The transformation temperatures are often referred to as critical temperatures and are observed by measuring changes in heat transfer or volume as specimens are heated or cooled. On heating, heat is absorbed and specimen contraction occurs as ferrite and cementite are replaced by the close-packed structure, austenite. On cooling, heat is evolved and specimen expansion occurs as austenite transforms to ferrite and cementite.

There are three critical temperatures of interest in the heat treatment of steel: the Ac1,which corresponds to the boundary between the ferrite-cementite field and the fields containing austenite and ferrite or austenite and cementite; the Ac3, which corresponds to the boundary between the ferrite-austenite and austenite fields; and the Acm, which corresponds to the boundary between the cementite- austenite and the austenite fields.

The transformations that occur at Ac1, Ac3, and Acm are diffusion controlled. Therefore, the critical temperatures are sensitive to composition and to heating and cooling rates. Rapid heating allows less time for diffusion and tends to increase the critical temperatures above those associated with equilibrium. Likewise, rapid cooling tends to lower the critical temperatures.

Generally, the critical temperatures for a given steel are determined experimentally. However, some empirical formulas that show the effects of alloying elements on the critical temperatures have been developed by regression analysis of large amounts of experimental data. For example, Andrews has developed the following formulas for Ac3 and Ac1 in degrees Celsius:$Ac3=910-203\sqrt{C}-15.2Ni+44.7Si+104V+31.5Mo+13.1W$;$Ac1=723-10.7Mn-16.9Ni+29.1Si+16.9Cr+290As+6.38W$. These formulas present another way of describing the effect of alloying elements on both the Fe-C diagram and the transformation behavior of steels. Elements that stabilize austenite lower the Ac3 and Ac1 as evidenced by their negative contributions to the corresponding equation, whereas elements that stabilize ferrite or carbide raise the Ac3 and Ac1 and make a positive contribution.

The carbon concentration will be distributed non-homogeneously in Austenite, if the heat treatment annealing temperature is located in between the Ac1 and Ac3, and the duration time is not sufficient. The later segregated carbon will accumulate in certain spots and the concentration will be higher than the surrounding area, these carbon compounds cannot dissolve into the Austenite solid solution structure and formed a spherical relict shape. The phase transformation occurs from $r \rightarrow \alpha$ when the Austenite is cool down slowly, the precipitated carbon show its outlook as spherical rather than layer type.

On the other hand, the homogeneous Austenite structure formed when the annealing temperature is too high or the duration time is too long, no matter how slow the cooling speed is taken, a strip shape of coarse pearlite structure will form and with a poor spherical annealing treatment. If the cooling speed is fast, then the strip carbon compounds rather than spherical shape will be precipitated. These poor heat treatments will result in the poor rolling property of the steel. A number of articles have been written about the mechanisms and kinetics of spheroidization(Chattopadhyay and Sellars, 1982; Robbin, Shepard and Sherby, 1964; Paqueton and Pineau, 1971). However, very little has been written about the details of the heat treatments.

3. Methodologies

The classic spherical annealing treatment sets the annealing temperature at 765°C with the duration time of 5.5-6.5 hours, after that, a rapid cooling to 735°C and then cool down to 680°C by the cooling speed of 10°C/hr.

3.1 Explanations of parameter selected:

Steel products of ASTM 4115-4140 are low alloy steels with the alloy elements of chromium (Cr) and Molybdenum (Mo), of which the annealing treatment models are the same. But owing to the high carbon content in ASTM 4140, the carbon release range (GK) reaches 4.5% maximum. Referring the Andrews regression formula ($Ac3=910-203\sqrt{C}-15.2Ni+44.7Si+104V+31.5Mo+13.1W$) shows the Ac3 become lower with the higher carbon content. The phase transformation temperature of Ac3 become lower, and the temperature gap in between Ac1 and Ac3 also become narrow. It results in the difficulties in targeting the exact treatment temperature, hence some products has been treated in the same process but showed unstable properties. The possible reasons may be due to the annealing temperature was too high or the duration time was too long. Hence, this study takes different approaches to lower down the temperature and shorten the duration time to avoid the formation of homogeneous Austenite and to promote the spherical annealing treatment. Besides, to locate the optimal cooling speed, the start and end point of cooling to ensure the hardness of the final product and minimize the qualities variation.

Annealing model design:

There are 6 controllable factors, which are annealing temperature, duration time, quench cooling rate, slow cooling rate, the start and end temperature of slow cooling . To consider the productivity and qualities after annealing, the duration time was set at 6 different levels to cover from 3.5 to 6.0 hours. The other factors are all with three levels, hence, an orthogonal array of $L_{18}(6^1 \times 3^5)$ was adopted for this study. Table 1 lists these factors and their alternative levels.

Table 1. The level table of heat treatment test factors

Sample	Control factor	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
A	Duration time(hr)	6.0	5.5	5.0	4.5	4.0	3.5
B	Annealing temperature(℃)	765	760	755			
C	Quench cooling rate(℃/hr)	30	20	10			
D	Start temperature of slow cooling(℃)	735	730	725			
E	Slow cooling rate(℃/hr)	10	8	6			
F	End temperature of slow cooling(℃)	680	675	670			

3.2 Experimental methods:

In this investigation, the grade of spheroidized structure was selected as a quality characteristics factor for bar-in-coil steel. For robustness and accuracy, each test was prepared two pieces.

37 pieces of as-rolled specimens with the dimension of ϕ *L = 22mm*250mm were tested in this experiment. One of those was treated as reference without annealing treatment. Each test used two pieces specimens, which were put in the different location (up and down) of

the annealing furnace. The tests were conducted by random sequence and then analyzed by Taguchi methods to optimize the annealing model.

3.3 Evaluation methods:

3.3.1 Metallurgy examination

The specimen without annealing treatment was etched by Nital, while the specimens after annealing treatment were etched by Picral. The specimens were classified into 6 grades (one to six, the lower the better) based on carbon compounds distribution of the spherical annealing treatment inspection standard .

3.3.2 Hardness test

The Rockwell Hardness Tester was applied to determine the hardness index. The specimen without annealing treatment was examined by HRc index (diamond cone with 120°, tip diameter of 0.2mm, with the load of 1471.0 N). The other specimens after annealing treatment were examined by HRb index (steel ball with the dimension of 1.5875mm, and the load of 980.7 N). Each specimen conducted two tests in a quarter position of the cross section.

4. Experimental results

In this study, six controllable factors were selected to optimize the spheroidized microstructure. Table 1 lists these factors and their alternative levels. An engineering experiment on the heat treatment process is conducted. Eighteen trials with two replications are conducted by a well-structured orthogonal array $L_{18}(6^1 \times 3^5)$. Table 2 summarizes the data of signal-to-noise ratio for the 18 trials. The experimental data are then employed for constructing the relationship model between parameters and responses through the BP neural network that 80% (approximately 15 samples) are used for training the neural network while the remaining 20%(approximately 3 samples) are used for testing.

4.1 Using Taguchi's approach

According to the response table as Table 3, the optimum levels of factors can be set as A2B2C2D1E1F2. The above analysis results showed the best spherical efficiency by using Taguchi S/N method indicated the optimal factors and levels are as followings. The optimal annealing temperature is 760°C, the duration time is 5.5 hours and then quenches to 735°C with cooling rate of 20°C/hr , following by a slow cooling to 675°C at the cooling rate of 10°C/hr.

Table 2. Data summary by experiment

Experiment no.	Factors						Degree of spheroidized structure	
	A	B	C	D	E	F	Average	S/N(dB)
1	1	1	1	1	1	1	2.25	-7.01
2	1	2	2	2	2	2	2.00	-6.99
3	1	3	3	3	3	3	3.25	-10.46
4	2	1	1	2	2	3	1.75	-4.95
5	2	2	2	3	3	1	1.25	-2.11
6	2	3	3	1	1	2	1.00	0.00
7	3	1	2	1	3	2	2.00	-6.28
8	3	2	3	2	1	3	2.25	-7.50
9	3	3	1	3	2	1	2.75	-8.82
10	4	1	3	3	2	2	1.25	-2.11
11	4	2	1	1	3	3	1.50	-3.98
12	4	3	2	2	1	1	1.50	-3.52
13	5	1	2	3	1	3	1.50	-3.52
14	5	2	3	1	2	1	1.00	0.00
15	5	3	1	2	3	2	3.25	-10.46
16	6	1	3	2	3	1	3.00	-10.51
17	6	2	1	3	1	2	1.25	-2.11
18	6	3	2	1	2	3	2.00	-6.02

Note: $\text{Average} = \frac{1}{n}\sum_{i=1}^{n} y_i$, $\text{S/NSTB} = -10\log_{10}(\frac{1}{n}\sum_{i=1}^{n} y_i^2)$, i = 1,2

For the 18 tests, the specimens after annealing treatment showed the hardness were in the range of 78.3-86.5 HRb, which fitted the specification requirement of hardness smaller than 87HRb. Therefore, the developed annealing model for hardness is provided for operation reference.

The reconfirmation tests based on the optimized factors and levels have been conducted for 37 runs. The test results showed the spherical efficiency for single treatment had fitted the quality control requirement of grade 1 to 2 (control limit for spherical efficiency should be smaller than 3).

4.2 Using Neural network approach

There were 6 input variables, 1 hidden layer, and 1 unit in the output layer. Therefore, the networks setting were defined as followings; the sigmoid as the conversion function, the delta rule as the learning role of target adjustment, the learning rate at 0.1 and the momentum at 0.9. Table 4 shows several options of the neural network architecture; in which the structure 6-2-1 under the best convergence criterion of the root of mean square (RMSE) is selected to obtain a better performance.

Table 3. S/N response table of grade of spheroidized structure

Control factor	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	Maximum-minimum
A	-8.18	-2.35	-7.54	-3.20	-4.66	-6.21	5.83
B	-5.75	-3.78	-6.55				2.77
C	-6.24	-4.74	-5.10				1.50
D	-3.90	-7.32	-4.86				3.42
E	-3.96	-4.81	-7.30				3.34
F	-5.34	-4.66	-6.07				1.41

Table 4. Options for Neural Networks

Architecture	RMSE	
	Training	Testing
6-2-1	0.1065	0.1813
6-3-1	0.0826	0.2931
6-4-1	0.0300	0.3975

There were 15 sets of the data obtained from the orthogonal testing results as the training base, and the root mean square error (RMSE) was the principle to examine the criteria of converged degree. The RMSE was also used to check the predicted precision by using another three sets of the data.

The optimal annealing temperature is 765°C, the duration time is 5.5 hours and then quenches to 727°C with the cooling rate of 10°C/hr, following by a slow cooling to 680°C at the cooling rate of 10°C/hr.

5. Conclusions

The objective of the heat treatment process is to develop a high level of spheroidized microstructure to satisfy customers. Heat treatment failures can result from many different causes. To achieve a high level of heat treatment performance and quality, the appropriate treatment process parameters must be accurately identified and controlled. The task of the process engineers is to identify and control these parameters to obtain desired heat treatment quality for optimizing response based on their experience or equipment provider's recommendation. Therefore, Many industry practitioners are trying hard to set up tests to model actual field conditions and the cause-effect relationship of design to performance; however, their knowledge to provide a nonlinear relationship between control parameters and responses, and to search the optimum parameter settings is limited. This task is complicated and difficult due to coupled multivariable system, which makes adjustment of any single parameter unavoidable without affecting the others. Therefore, we adopt Taguchi methods and Neural networks that can evaluate the process and determine the best adjustments.

The re-treatment of bar-in-coil steel by spherical annealing process in 2000 was 3% of the total production. After establishing the optimal annealing model by Taguchi $L_{18}(6^1*3^5)$ experimental design, and tracing the 37 batches operation, the re-treatment tonnage has reduced to zero, which fully fit the requirement target of 1.5%. Besides, adopting the neural networks also developed the optimal annealing model and spherical efficiency at 1.5 degree (fully fit the control limit of less than 3 degree).

Engineers conventionally apply the Taguchi methods to optimize the process; however, the Taguchi methods has some limitations in practices. For example, this method can only get the optimal solution under discrete factors that will lead the real optimum with uncertain. Advantages of the neural networks are their easy-and-quick capability to explore a nonlinear multivariate relationship between parameters and responses.

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