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Research article

Process Parameter Optimization of Ti-45Nb Titanium Alloy Produced Using the Design of Experiments Technique

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Abstract: The goal of this study is to optimize the production conditions of Ti-45Nb titanium alloy by innovatively introducing the Design of Experiments (DOE) method and using the 2^k method of full factor analysis in DOE, and to improve the chemical heterogeneity of Ti-45Nb titanium alloy by analyzing and optimizing the parameter conditions of the production process and a total of 32 experiments was conducted. Ti-45Nb titanium alloy was produced by vacuum arc remelting (VAR) according to the following process parameters. The titanium alloy products obtained from each production were cut into circular samples with a diameter of 16 cm, and the chemical inhomogeneity was measured by Energy-dispersive X-ray spectroscopy using the 5-point sampling method. Then, the chemical inhomogeneity data values were entered into the previous experimental design, and the appropriate factor levels were determined using the technology provided in the Minitab statistical software package, with a significance level of 0.05 (α = 0.05). Through full factorial design (DOE) and residual analysis, a regression model for chemical inhomogeneity was successfully constructed. After optimization, the production conditions of Ti-45Nb titanium alloy are: Smelting current (KA) = 1.7, Current coil (A) = 3.2542, Transform time (S) = 6, Inlet water temperature (°C) = 25, and Water flow (L/min) = 220. The chemical inhomogeneity value of the produced Ti-45Nb titanium alloy is theoretically 10%. It can provide a reference for enterprise production.

Keywords: Ti-45Nb ritanium alloy; chemical inhomogeneity; design of experiments; 2^k full factorial method; parameter optimization

1. Introduction

Titanium is a metal element with excellent mechanical properties and low density. It is widely distributed in various minerals and is abundant in the Earth's crust. Titanium is a chemical element with the symbol Ti and atomic number 22. Sometimes called the "space age metal" [1]. There is probably no material more closely associated with aerospace than titanium and its alloys [2].

Titanium alloys exhibit exceptional physical and mechanical properties [3]. However, many titanium alloys have been developed [4]. Due to their high specific strength and extraordinary corrosion resistance, titanium alloys are widely used in engineering, particularly in the aerospace, automotive, and biomedical fields [5,6]. Currently, the titanium alloy industry appears mature, yet new technologies and applications for these alloys continue to emerge [7]. Despite the utility of titanium alloys, the number of articles addressing the subject has been limited [8]. The development of new titanium alloy materials is complex, and their production and optimization are even more challenging. Today, the demand for titanium alloys far exceeds their production capacity. The demand for titanium is expected to continue to increase [9]. This inevitably leads to high production costs for titanium alloys, particularly for new materials such as Ti-45Nb.

Ti-45Nb is a titanium alloy composed of titanium (Ti) and niobium (Nb). The alloy typically contains 45% niobium by weight. Because niobium (Nb) is a biocompatible alloying element [10], the new titanium alloy Ti-45Nb was primarily used for biomedical applications upon its invention [11–13]. However, other strategic industries also require advanced titanium alloys. Modern technological advancements are placing increasingly high demands on the functional performance of new structural materials. Currently, titanium and titanium-niobium alloys are key materials in strategic industries such as aerospace, rocket technology, nuclear energy, shipbuilding, medicine, food and chemical engineering, and electronics, and in many cases, are irreplaceable [14–16]. The combination of titanium and niobium in the Ti-45Nb titanium alloy imparts excellent mechanical strength, low density, and corrosion resistance, making it suitable for a variety of applications, from aerospace to medical devices. In the aerospace industry, it is primarily used to manufacture ultra-high-strength components, such as aircraft rivets and engine components. At the same time, titanium alloys have low thermal conductivity and high chemical reactivity, which makes machining more challenging. As a new aviation titanium alloy [17], Ti-45Nb is even more challenging to produce. However, despite its desirable properties, Ti-45Nb is generally perceived as a high-cost material. Producing Ti-45Nb titanium alloy requires significant effort and cost, underscoring the urgent need to improve its manufacturing sustainability.

The vacuum arc remelting method is a promising, innovative approach that combines the benefits of thermochemical and electrochemical processes. This technique has emerged as an economically viable and environmentally friendly solution for titanium production. The vacuum arc remelting method is well-suited to producing the Ti-45Nb titanium alloy. However, because there are too many process parameters to control during the production of this new material, traditional production methods often require experience and experimentation to determine appropriate settings. Multiple tests of each parameter and experience-based judgments are time-consuming, thereby reducing production efficiency and increasing production costs. This is undoubtedly a further blow to the new titanium alloy Ti-45Nb, which is already priced at a premium.

The innovative application of the design of experiments (DOE) method addresses the limitations of traditional experiments in terms of cost and parameter coverage. In this study, a non-factorial design was employed to improve the efficiency of the Ti-45Nb titanium alloy by optimizing process parameters (without structural changes), thereby increasing yield [18].

2. Materials and Methods

This study conducted a production experiment for a novel material, carefully selecting suitable equipment and manufacturing techniques based on widely available raw materials, namely the Ti-45Nb titanium alloy. The objective was to enhance production efficiency through a creative strategy that utilized a newly developed design-of-experiments methodology.

2.1 Materials

The primary materials utilized in this study are titanium and niobium. By welding these metals at a 55% titanium to 45% niobium mass ratio and remelting the resulting alloy, a novel material, Ti-45Nb, is produced.

2.2 Methods

This research investigated the application of a fuzzy logic system to identify suitable parameters to produce the Ti-45Nb titanium alloy. Initially, the variables to be tested were defined, followed by applying the 2^k method within a design-of-experiments framework to estimate and optimize the parameters. The study identified the most effective operating conditions and conducted yield-performance tests. The research methodology was systematically structured, as illustrated in Figure 1. As depicted in Figure 1, the research followed a well-defined sequence of steps summarized below.

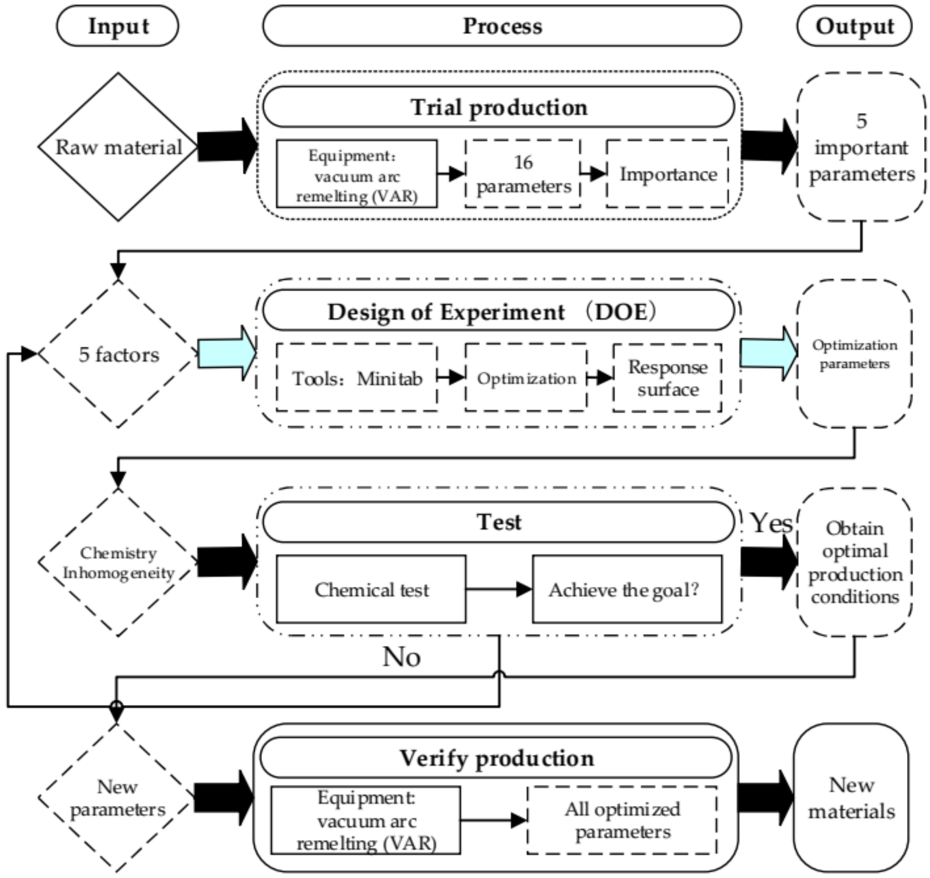

Figure 1. Research path and conceptual framework.

Referring to Figure 1, the path and conceptual framework of this research comprise the following: Input, Process, and Output. The conceptual framework of this research is structured into the following steps. The first step involves input, starting from raw materials and proceeding through the Trial Production process, which is further divided into three steps. The vacuum arc remelting (VAR) equipment is used for trial production, and all 16 parameters are used to determine their importance. This research investigates the factors of smelting current, current coil, transforming time, inlet water temperature, and water flow, as these variables represent the primary controllable parameters governing the energy balance, heat transfer, and melt pool flow dynamics of the smelting process. These factors directly influence the material's homogeneity, defect formation, and microstructural development, and are clearly definable and controllable through the process control system. The selection of these parameters follows established Design of Experiments (DOE) methodology, beginning with a comprehensive review of the literature and process knowledge, complemented by preliminary experimental observations to identify factors with clear mechanistic relevance and observable effects on process outcomes. Subsequently, statistical screening was employed to reduce the dimensionality of the parameter set, yielding a focused set of high-impact factors suitable for interaction analysis under practical constraints on experimental cost, safety, and process stability.

The output comprises 5 essential parameters and serves as input to the second step, which includes 5 factors. In the second step, starting from the input of 5 factors, the specific process is optimized using the Design of Experiment (DOE) method, which is divided into three steps. The Minitab tool is used to optimize and obtain a response. The output is a response parameter that serves as input to the third step, chemist inhomogeneity. In the third step, starting from the input Chemist inhomogeneity, the specific process is tested in two steps. Through chemical tests, it is determined whether the target has been achieved. If achieved, the optimal production conditions are obtained. If it has not been completed, it is returned to the second step for further optimization. In the fourth step, the optimized production parameters are used as inputs. The specific process involves verifying production, which is divided into two steps. The production is validated using vacuum arc remelting (VAR) equipment, and all optimized parameters are employed to produce output as new materials.

2.2.1 Tool and Equipment

The experimental design was developed in Minitab, and VAR equipment was employed during the process. A pilot trial was conducted with the VAR system to establish preliminary parameters. According to the experimental design, production was performed using the VAR unit, with adjustments to critical process parameters. Raw material inputs and product yields were measured and analyzed both before and after production. This evaluation aimed to assess the feasibility of the treatment method and to identify the optimal process conditions.

2.2.2 Set factor input variables through experimental design

The initial phase involves establishing input variables through an experimental design [19]. There are sixteen smelting process conditions for titanium alloys: Smelting current, Smelting voltage, Welding current, Welding voltage, Current coil, Transform time, Vacuum before welding, Boost rate, Vacuum before smelting, Crucible ratio, Stable arc current, Smelting Vacuum, Inlet water temperature, Outlet water temperature, Water flow, and Cooling time.

Before starting the preliminary trials, first exclude two fixed parameters, such as the Crucible ratio and the Stable arc current. And then exclude welding parameters unrelated to melting, such as welding current and welding voltage, as well as parameters before melting, such as Vacuum before welding and Vacuum before smelting. Then, through preliminary trials, determine the importance, control difficulty, and control effect order of 10 parameters. In the early stages of the trials, it was found that Smelting voltage varies with Smelting current; therefore, the Smelting voltage was excluded from the analysis. Similarly, Outlet water temperature varies with Inlet water temperature; hence, exclusion was also carried out. In subsequent preliminary trials, it was found that the vacuum parameters included the Boost rate and the Smelting Vacuum. In contrast, the Cooling time was difficult to control and had little impact on the product. Therefore, the remaining five parameters were selected for further research. Based on a thorough analysis of parameters and successful trial production, a set of five key parameters was identified from the initial pool of 16 variables. These parameters were selected for their high significance in the process and their controllability, making them ideal input factors. The identified parameters are as follows: Smelting Current, Current Coil, Transform Time, Inlet Water Temperature, and Water Flow. These parameters were selected based on their significant impact on the process and ease of control. By carefully adjusting and optimizing these parameters, manufacturers can improve the quality and performance of the final product. Therefore, setting them as factors. Each factor and their specific details are as follows: Smelting current (KA) with a range of 1.4-2.0, Current coil (A) with a range of 1-4, Transform time (S) with a range of 3-6, Inlet water temperature (°C) with a range of 25-31, and Water flow (L/min) with a range of 160-220.

F = Smelting current, Current coil, Transform time, Inlet water temperature, Water flow.

Factor 1: Smelting current (KA)

Factor 2: Current coil (A)

Factor 3: Transform time (S)

Factor 4: Inlet water temperature (°C)

Factor 5: Water flow (L/min)

These factors are categorized into two levels.

Sc = Smelting current. The Smelting current (Sc) is divided into two levels. The low-level Smelting current is set at 1.4KA, while the high-level Smelting current is set at 2KA.

Cc = Current coil. The Current coil (Cc) is divided into two levels. The low-level Current coil is set at 1A, while the high-level Current coil is set at 4A.

Tt = Transform time. The Transform time (Tt) is divided into two levels. The low-level Transform time is set at 3S, while the high-level Transform time is set at 6S.

Iw = Inlet water temperature. The Inlet water temperature (Iw) is divided into two levels. The low-level Inlet water temperature is set at 25℃, while the high-level Inlet water temperature is set at 31℃.

Wf = Water flow. The Water flow (Wf) is divided into two levels. The low-level Water flow is set to 160 L/min, while the high-level Water flow is set to 220 L/min.

Table 1. Factor settings.

No	Factor	Low	High	Unit
1	Smelting current	1.4	2	KA
2	Current coil	1	4	A
3	Transform time	3	6	S
4	Inlet water temperature	25	31	℃
5	Water flow	160	220	L/min

Table 1 presents the parameter composition and levels, highlighting how the experimental design elucidates the interrelationships among these parameters. By specifying the variables for each trial, a second-order factorial, categorized as low and high [20], is employed to ensure the precision of the experimental design's parameters and levels. This study employed a full factorial design using the 2^k method, with 32 experiments conducted. Subsequent experiments will be structured based on the inputs above. Through these experiments, the experimental variables and levels influencing chemical heterogeneity were identified. The objective is to analyze and optimize operational parameters effectively.

2.2.3 Characterization method

To characterize the process, following the experimental design outlined above, Ti-45Nb titanium alloy was produced in a VAR furnace using a sequential set of process parameters. After each production run, the resulting titanium alloy product was formed into a circular specimen measuring 16 cm in diameter. After surface treatment, chemical inhomogeneity was measured using a five-point sampling method, including the center of the circle, a horizontal and a vertical line passing through the center, and the intersection of five equally divided circles. The specific sampling points are shown in Figures 2 and 3 below:

Figure 2. Ti-45Nb titanium alloy product sample.

According to the test regulations for chemical inhomogeneity, the principle of not measuring the base metal, titanium, in the Ti-45Nb titanium alloy means that its inhomogeneity is not measured. Therefore, this study selects niobium as the target for inhomogeneity measurement. The determination of niobium in metals is performed using energy-dispersive X-ray spectroscopy (EDS), which measures the energy spectrum of X-ray reflections from the material. In energy-dispersive X-ray spectroscopy, ω is usually used to represent the percentage of the element content in the sample. ω refers to the content of an element in a substance calculated in units of mass fraction, which is the ratio of the maximum mass of a particular component in the substance to the mass of the entire substance.

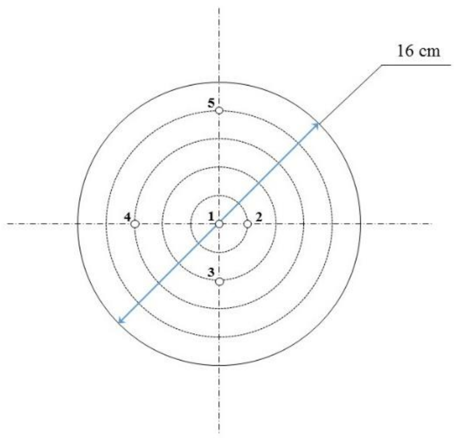

Figure 3. Ti-45Nb titanium alloy product sample test point.

According to the standard for chemical inhomogeneity of titanium alloys, the standard content of niobium in Ti-45Nb titanium alloy is 45. Therefore, the chemical inhomogeneity deviation value of Ti-45Nb titanium alloy in this study is the content of niobium measured by the sample, that is, the absolute value of the difference between the niobium content ω of each sample and 45, and then divided by 45; the chemical inhomogeneity value of Ti-45Nb titanium alloy in this study can be obtained. The specific formula is as follows: Formula 1:

$$CI_i = \frac{\omega_i - 45}{45} \tag{1}$$

In accordance with the previously planned experimental design, production was carried out in the specified sequence. The 32 Ti-45Nb titanium alloy product samples produced were tested using the 5-point sampling method previously defined, and 160 niobium contents (ω) were obtained. Then, they were calculated using formula 4-1 to receive the chemical inhomogeneity values for each sampling point across all products. Then, the chemical inhomogeneity data for the five sampling points of each product were averaged to obtain the chemical inhomogeneity data for the Ti-45Nb titanium alloy produced each time.

3. Results and Discussion

3.1 Results of the experiment

The chemical inhomogeneity data were incorporated into the experimental design, and the effects of the five factors on the chemical inhomogeneity of Ti-45Nb titanium alloy were evaluated using the previously established design method. In an experiment conducted under full-factorial design conditions, the five process parameters affecting the chemical inhomogeneity of Ti-45Nb titanium alloy were analyzed. In 32 experiments, the appropriate factor level was determined using the best technique provided by Minitab, with a significance level of 0.05 (α = 0.05). The full factorial experiment included 32 trials, and the results were used to determine the relationship between the five process parameters and the chemical inhomogeneity of Ti-45Nb titanium alloy, as shown in Table 2. The full factorial design method was used for experimental structure design. Table 2 summarizes the experimental results and highlights the key operational parameters identified. These parameters were evaluated using statistical analysis in Minitab across 32 experiments. The findings provide a foundation for an in-depth analysis of the process parameters and experimental data.

Table 2. Results of the experiment to determine the five process parameters.

Run Order	Std Order	Smelting current	Current coil	Transform time	Inlet water temperature	Water flow	Chemical inhomogeneity
1	25	1.4	1	3	31	220	20.08
2	21	1.4	1	6	25	220	16.98
3	2	2	1	3	25	160	11.46
4	22	2	1	6	25	220	9.03
5	30	2	1	6	31	220	10.05
*	*	*	*	*	*	*	*
*	*	*	*	*	*	*	*
*	*	*	*	*	*	*	*
28	18	2	1	3	25	220	11.04
29	31	1.4	4	6	31	220	13.97
30	8	2	4	6	25	160	5.49
31	11	1.4	4	3	31	160	16.46
32	6	2	1	6	25	160	9.52

3.2 The analysis of experimental results

The first step in the data analysis is to plot the yield residuals. This is illustrated in Figure 4, which shows the residual plot.

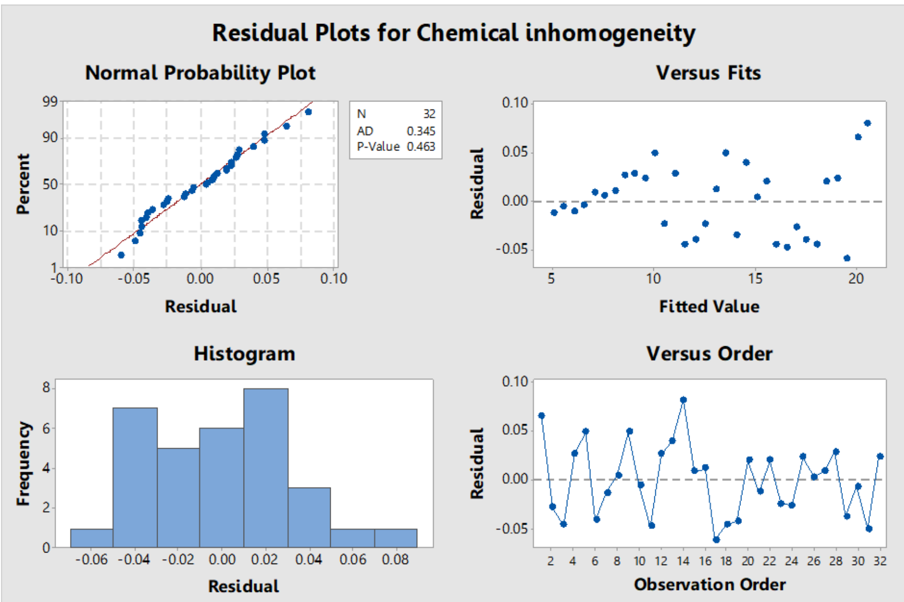

Figure 4. Residual Plots for Chemical Inhomogeneity.

According to the figure, most points are distributed along the diagonal, with only a slight deviation at the end. Specific indicators include N (sample size) is 32, indicating that the sample size is sufficient and the statistical results are credible. The Anderson-Darling (AD) statistic is 0.345, and the sample size is small, indicating good normality. The P-value is 0.463, which exceeds the 0.05 significance level, indicating that the normality assumption cannot be rejected. The histogram of the residuals is approximately symmetrical, bell-shaped, and concentrated near zero. This shows that the residuals are well distributed and supports the standard distribution hypothesis.

The data in this figure are first standardized. Based on the Normal Probability Plot and Histogram, the residuals meet the standard distribution assumption. The Anderson-Darling statistic is small (0.345), and the P-value is greater than 0.05 (0.463), further supporting this conclusion. Second, the research data is independent. From the Residuals vs. Order plot, the residuals are independent of experimental order, and there is no systematic trend or cyclical fluctuation. Third, the data have equal variance. From the Residuals vs Fits plot, the residual distribution appears random and uniform, and the model satisfies the equal-variance assumption. Based on the above conclusions, the model-fitting effect can be analyzed. Residual analysis showed that the model fit the data to some extent. The residuals were normally distributed and showed no apparent pattern, supporting the model's validity. The residuals met the assumptions of normality, independence, and homogeneity of variance, indicating good model fit and high-quality experimental data. The current results support the stability of the experimental design and model, enabling prediction and further optimization of experimental conditions.

Table 3. This is a table. Tables should be placed in the main text near the first time they are cited.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	682.851	136.570	87003.39	0.000
Linear	5	682.851	136.570	87003.39	0.000
Smelting current	1	512.640	512.640	326582.42	0.000
Current coil	1	128.000	128.000	81543.64	0.000
Transform time	1	32.281	32.281	20564.68	0.000
Inlet water temperature	1	7.980	7.980	5083.74	0.000
Water flow	1	1.950	1.950	1242.47	0.000
Error	26	0.041	0.002		
Total	31	682.892			

Evaluation of the four operational parameters in the experimental design highlights the factors affecting yield under the specified analysis conditions, as shown in Table 3. According to Table 3, it can be concluded that by comparing the sum of squares of Model and Total, we can see that the model explains almost all the total variation, indicating the model is effective, the sum of squares of error and mean square of error are tiny, proving that the experimental design and model fitting are accurate. The results of the full-factorial experiment, comprising all 32 runs, were also presented within a yield analysis-of-variance framework. Factors influencing yield can be identified at the $\alpha = 0.05$ significance level. When the main factors were considered significant, these factors included Smelting current, Current coil, Transform time, Inlet water temperature, and Water flow. Given the rationality of this experimental design and the favorable results obtained, it is appropriate to incorporate these findings into subsequent production experiments to enhance yield and identify more optimal experimental conditions.

3.3 Response optimizer results

According to the requirements of China's titanium alloy production standard GB/T 3620.2-2023, "Allowable Deviation of Chemical Composition of Titanium and Titanium Alloy Processing Products," and the conventional requirements of titanium alloy production enterprises, the chemical inhomogeneity standard of titanium alloy is usually set at 10%. By incorporating this target value into the optimization, we can determine the optimal production parameters for the Ti-45Nb alloy, thereby meeting the 10% standard. The optimized results are shown in Figure 5, Optimization Plot: From the optimal results shown in Figure 5, by analyzing the production process parameter conditions of Ti-45Nb titanium alloy, it can be concluded that the production process parameters of Ti-45Nb titanium alloy after optimization are as follows: Smelting current (KA) = 1.7, Current coil (A) = 3.2542, Transform time (S) = 6, Inlet water temperature (°C) = 25, and Water flow (L/min) = 220. -optimized towards the target yield.

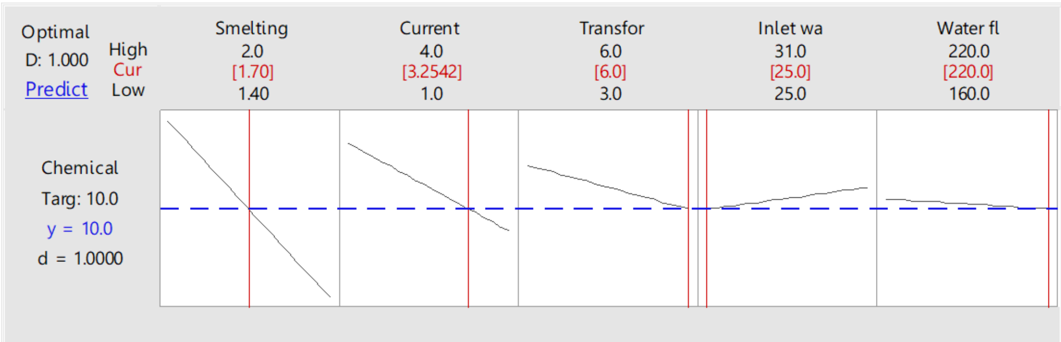

Figure 5. Illustrates an analysis of the yield level at the specified optimal value.

3.4 Verification of research results

Using the optimized production parameter conditions for the Ti-45Nb alloy, the process was repeated, and the resulting product was subjected to a chemical inhomogeneity test using the same method. The results were used to verify whether the final optimization process met the requirements. After production according to the required process parameters, the data results obtained are shown in Table 4 below:

Table 4. The optimized test data.

Run Order	Point 1 data	Point 2 data	Point 3 data	Point 4 data	Point 5 data
After optimization	55.00 %	55.01 %	54.99 %	54.99 %	55.02 %

The data in Table 4 can be used to calculate the chemical inhomogeneity of representative Ti-45Nb titanium alloy products produced with optimized production using Formula 1. The details are shown in Table 5:

Table 5. The average value of data deviation after optimization.

Run Order	Absolute deviation					Average
	Point 1	Point 2	Point 3	Point 4	Point 5	
After optimization	10.00 %	10.01 %	9.99 %	9.99 %	10.02 %	10.002 %

The last column of Table 5 is the average value of the absolute value of all data deviations measured at the five test points of the Ti-45Nb titanium alloy after optimized production, which is the representative data value of the chemical inhomogeneity of the Ti-45Nb titanium alloy after optimized production. The true nature of the chemical inhomogeneity of the Ti-45Nb alloy after optimized production can inform subsequent analyses of production conditions and verification. According to the results, the ω value of the chemical inhomogeneity of the Ti-45Nb titanium alloy after optimized production is 10.002%, which differs by 0.02%

from the theoretical value of 10.00%. Within the error range, the optimized process conditions are considered to meet the set requirements. The optimization results are reasonable and acceptable, demonstrating that the Ti-45Nb titanium alloy production model exhibits good linearity, that the results can be predicted and reproduced, and that the model is correctly and appropriately established.

3.5 Other performance tests of target material products

For the Ti-45Nb titanium alloy products that meet the chemical inhomogeneity requirements after optimization, to further verify whether the products fully meet the performance requirements of Ti-45Nb titanium alloy products, after completing the niobium element detection, comprehensive element detection, and microstructure detection were continued on the Ti-45Nb titanium alloy product samples with the optimized chemical inhomogeneity ω of 10.002%. First, a comprehensive elemental analysis was conducted on the optimized Ti-45Nb titanium alloy samples to determine the contents of impurity elements, including carbon, oxygen, nitrogen, and hydrogen. The specific situation is shown in Table 6, Chemical Element Analysis.

Table 6. The chemical element analysis.

Sample No.	C (ω%)	O (ω%)	N (ω%)	H (ω%)
After optimization	0.012	0.031	0.007	0.0003

According to the data given in the chemical element analysis table in Table 6, in the optimized Ti-45Nb titanium alloy product sample, the carbon content ω is 0.012%, the oxygen content ω is 0.031%, the nitrogen content ω is 0.007%, the hydrogen content ω is 0.0003%, and other elements cannot be detected due to their low content. This result indicates that, following elemental analysis, the optimized Ti-45Nb titanium alloy product sample contains impurity elements at levels below the required lower limit, fully meeting the requirements for titanium alloy products and therefore qualifying. At the same time, it can be shown that the production optimization does not introduce additional interference, that the optimization model is feasible, and that the optimization process is reasonable. Following chemical elemental analysis, the second step is to conduct microstructural characterization of the optimized Ti-45Nb alloy samples. The method involves scanning and imaging the titanium alloy microstructure at 50x and 200x magnifications using a scanning electron microscope. The material's microscopic properties are then assessed based on the lattice distribution observed in the image. The specific microstructure diagram is shown in Figure 6.

Figure 6. Microstructure of the Ti-45Nb titanium alloy sample.

From the microstructural diagram in Figure 6, it can be concluded that the optimized Ti-45Nb alloy sample exhibits a precise microstructure, clear lattice boundaries, and a uniform distribution. This result indicates that the microstructure of the optimized Ti-45Nb alloy sample meets the standard requirements for titanium alloys and fully satisfies the criteria for titanium alloy products, thereby qualifying the product. At the same time, it can also demonstrate that production optimization has no adverse effects on the microstructure, that the optimization model is correct, and that the optimization process is appropriate.

3.6 Full parameter range expansion optimization method

To broaden the applicability of this research, guide similar studies, and assist other titanium alloy manufacturers in adopting the same techniques and processes, this study will extend the target-point optimization results to cover the entire parameter range of the production process, providing a basis and ideas for further research and production.

3.6.1 Regression equation

The first step is to find the regression equation of the Ti-45Nb titanium alloy production process. The relationships among the parameters can be determined from the previous data analysis, and the regression equation can be derived. The regression equation can evaluate the chemical inhomogeneity of Ti-45Nb titanium alloy products under any conditions.

The regression equation for the uncoded units is given in Formula 2.

$$\text{Chemical inhomogeneity} = 38.6863 - 13.3417\ \text{Smelting current} - 1.33333\ \text{Current coil} - 0.66958\ \text{Transform time} + 0.16646\ \text{Inlet water temperature} - 0.008229\ \text{Water flow}. \quad (2)$$

Formula 2 can be used to derive chemical heterogeneity data for the product obtained under any production parameter conditions during Ti-45Nb production, providing guidance for related research and supporting other titanium alloy production companies.

3.6.2 Interaction plot and Main Effects plot

Based on the previous data analysis and the model established in Formula 2, the second step is to construct the interaction and central-effect diagrams for the production conditions of Ti-45Nb. This diagram illustrates the interactions and influences among various production process parameters and identifies the main effect. The details are shown in the Interaction plot of Figure 7 and the Main Effects plot of Figure 8.

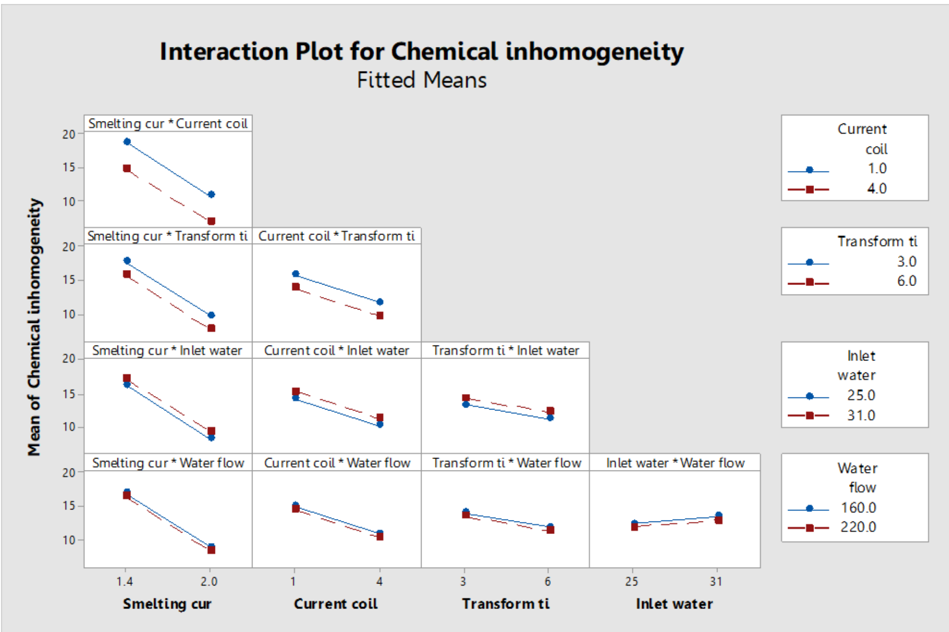

Figure 7. Interaction plot for Chemical inhomogeneity.

According to Figure 7, trends in each process parameter during the production of Ti-45Nb titanium alloy are discernible, and the mutual influence between any two parameters can also be analyzed. Other researchers and titanium alloy manufacturers can obtain the specific ranges and values of each parameter from it.

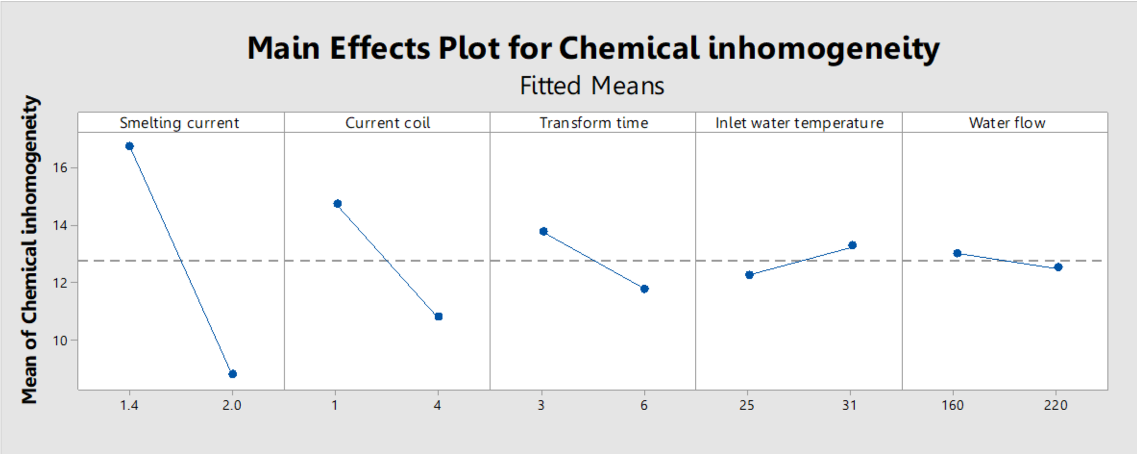

Figure 8. Main Effects of the plot for Chemical inhomogeneity.

Figure 8 shows the details of each process parameter used in the production of the Ti-45Nb titanium alloy, including the parameter's size change and range. According to Figure 17, the slopes of the influence value lines for each parameter differ, with larger slopes indicating greater impact on the product's chemical inhomogeneity and thus a more critical main effect. Based on the slopes of the five parameters, the Smelting current exhibits the largest slope, indicating it is the most significant main effect, followed by the Current coil, Transform time, Inlet water temperature, and Water flow. The effect direction of each process parameter on the result can also be judged according to the inclination direction of each parameter line segment, among which Smelting current, Current coil, Transform time, and Water flow are adverse effects; that is, the larger the parameter, the smaller the chemical inhomogeneity of the product, while Inlet water temperature is a positive effect, that is, the larger the parameter, the greater the chemical inhomogeneity of the product. Different effect directions mean opposite operation directions. Other researchers and manufacturers of titanium alloys can conduct research and operations based on this to avoid wasting time and costs.

3.6.3 Contour plot

According to the model established in Formula 2, the third step is to generate a contour plot of the production conditions for the Ti-45Nb titanium alloy. This map enables a more intuitive assessment of how different parameters influence the product's chemical heterogeneity than the equation, and it provides guidance for titanium alloy research and production based on the information it presents. The specific information is shown in Figure 9-18 below. Among them, Figures 9-12 pertain to Smelting Current. Figures 13 to 15 are related to the Current Coil. Figures 16 and 17 pertain to Transformation Time. Figure 18 is associated with Inlet Water Temperature. Figure 9 shows that the relationship between Current Coil and Smelting Current is proportional, meaning that increasing both parameters reduces Chemical Inhomogeneity. The color blocks in the figure indicate that the closer to dark blue, the smaller the Chemical Inhomogeneity, and the closer to dark green, the larger it is. The optimal position is near blue.

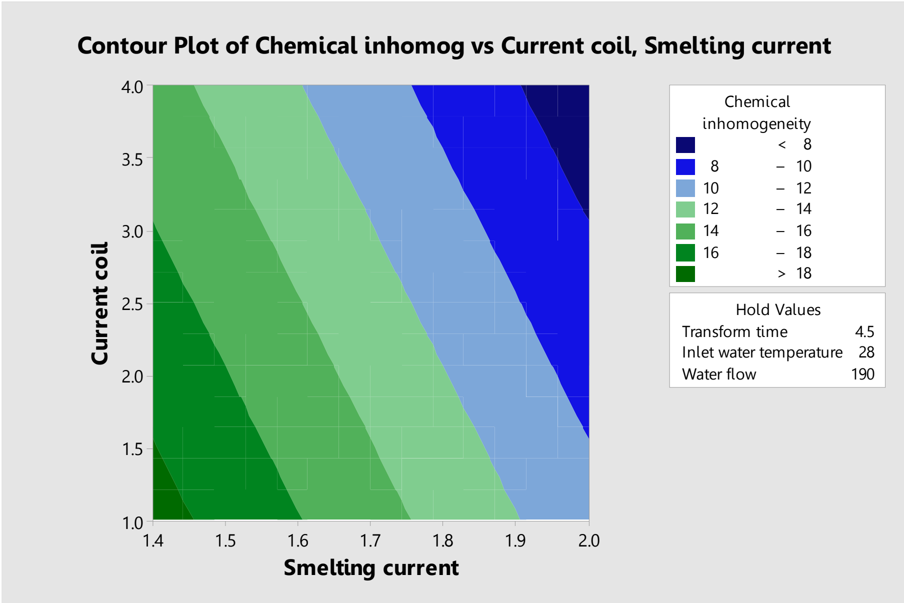

Figure 9. Contour Plot for Current Coil and Smelting Current on Chemical Inhomogeneity.

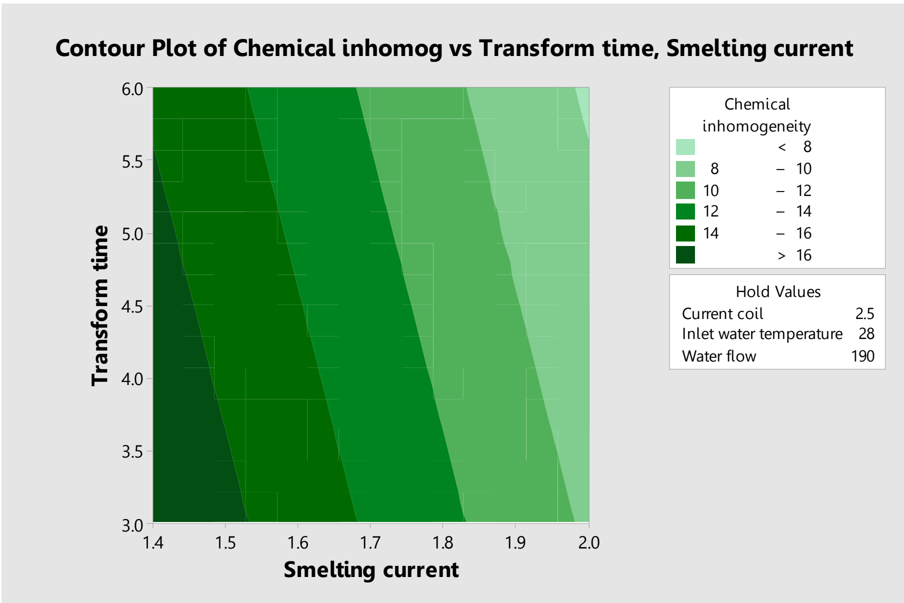

Figure 10. Contour Plot for Transform Time and Smelting Current on Chemical Inhomogeneity.

Figure 10 shows that Transform Time and Smelting Current are directly proportional; increasing both parameters reduces Chemical Inhomogeneity. The color blocks in the figure indicate that the closer to light green, the smaller the Chemical Inhomogeneity, the closer to dark green, the larger the Chemical Inhomogeneity. The optimal position is near light green. Figure 11 shows that the relationship between Inlet Water Temperature and Smelting Current is inversely proportional. That is, increasing Smelting Current and decreasing Inlet Water Temperature can reduce Chemical Inhomogeneity. The color blocks in the figure indicate that the closer to light green, the smaller the Chemical Inhomogeneity, the closer to dark green, the larger the Chemical Inhomogeneity. The optimal position is near light green.

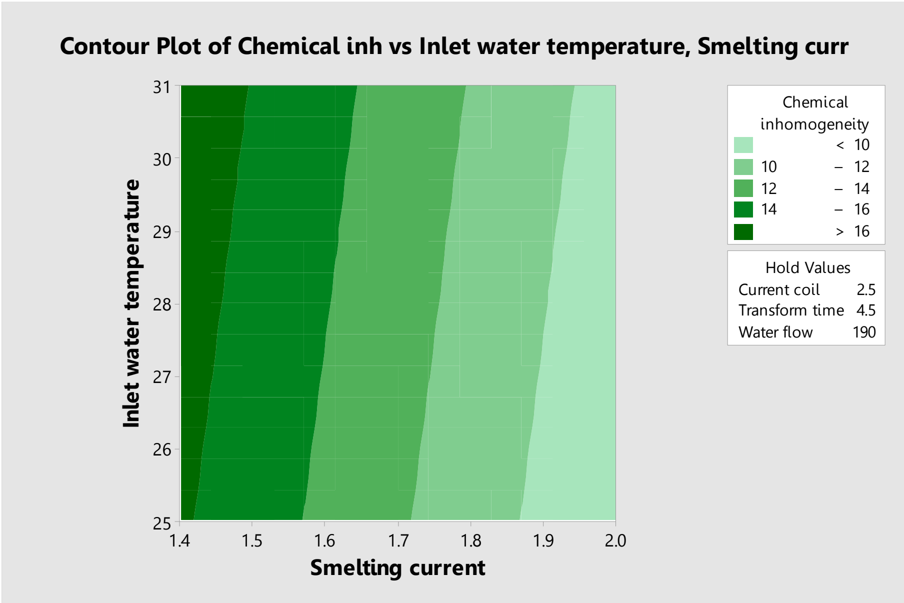

Figure 11. Contour Plot of Inlet Water Temperature and Smelting Current with Respect to Chemical Inhomogeneity.

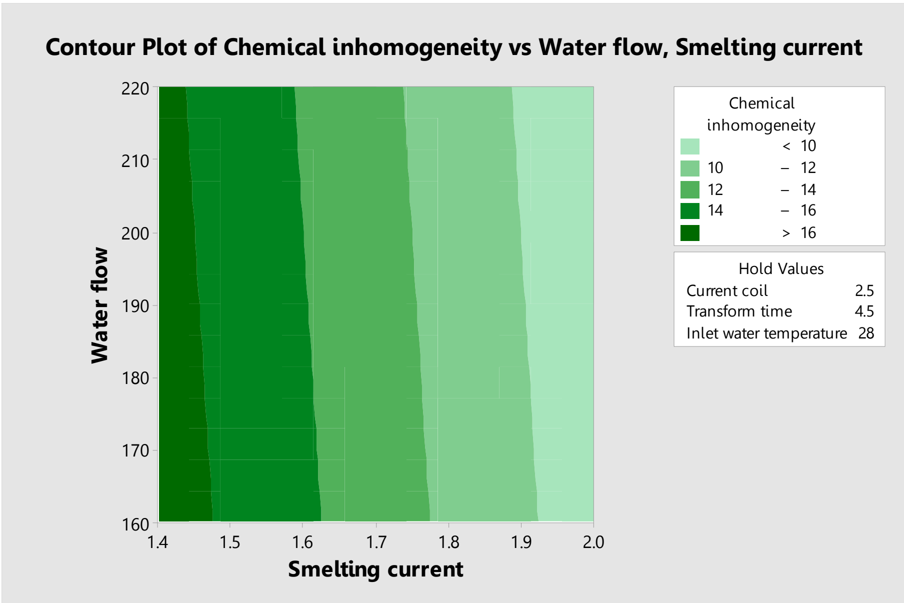

Figure 12. Contour Plot of Water Flow and Smelting Current in the Presence of Chemical Inhomogeneity.

Figure 12 shows that the relationship between Water Flow and Smelting Current is proportional. That is, increasing Smelting Current and Water Flow can reduce Chemical Inhomogeneity. However, the slope is nearly vertical, indicating that the effect of Water Flow is substantially less significant than that of Smelting Current. The color blocks in the figure suggest that the closer to light green, the smaller the Chemical Inhomogeneity, the closer to dark green, the larger the Chemical Inhomogeneity. The optimal position is near light green. The four figures above illustrate the relationship between adjustments to production parameters and the smelting current. They also demonstrate the relationship between other production parameters and smelting current. Except for the inlet water temperature, all other parameters are directly proportional to the smelting current, with varying slopes. The closer the linear relationship is to vertical, the less influential the parameter. Companies can choose production parameter adjustment methods based on chemical inhomogeneity requirements and specific color blocks.

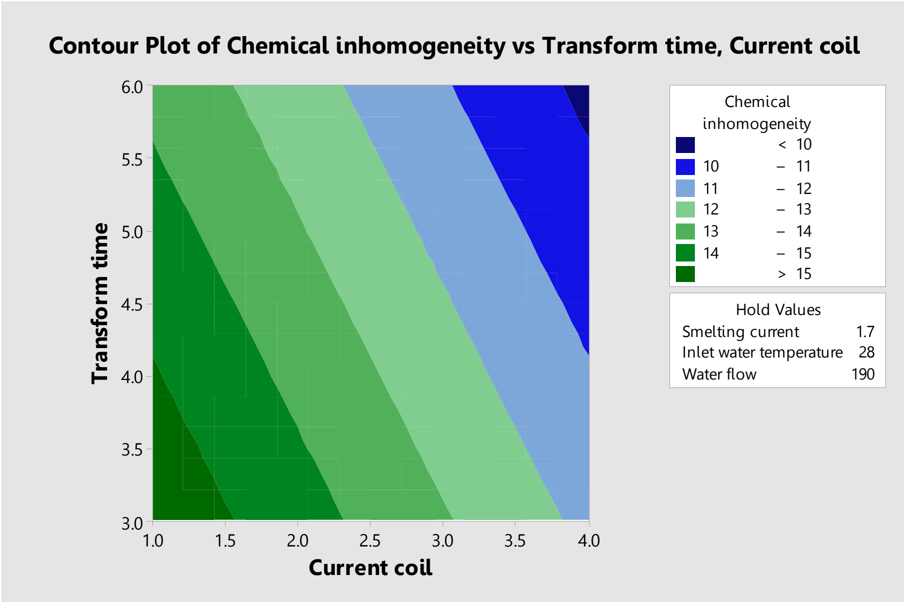

Figure 13. Contour Plot of Transform Time and Current Coil for Chemical Inhomogeneity.

Figure 13 shows that Transformation Time and Current Coil are directly proportional. Increasing the Current Coil and Water Flow reduces Chemical Inhomogeneity. The color blocks in the figure indicate that chemical inhomogeneity decreases as the color approaches dark blue and increases as the color approaches dark green. The optimal value is nearly blue.

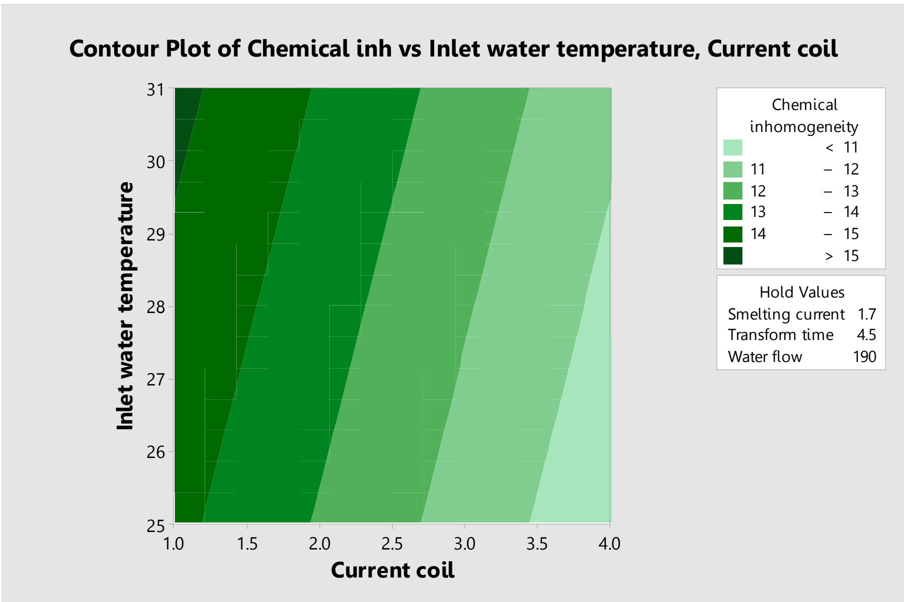

Figure 14. Contour Plot for Inlet Water Temperature and Current Coil on Chemical Inhomogeneity.

Figure 14 shows that the relationship between Inlet Water Temperature and Current Coil is inversely proportional. That is, increasing the Current Coil and decreasing the Inlet Water Temperature can reduce Chemical Inhomogeneity. The color blocks in the figure indicate that the closer the color is to dark green, the smaller the Chemical Inhomogeneity; the farther from dark green, the larger the Chemical Inhomogeneity. The optimal position is near light green.

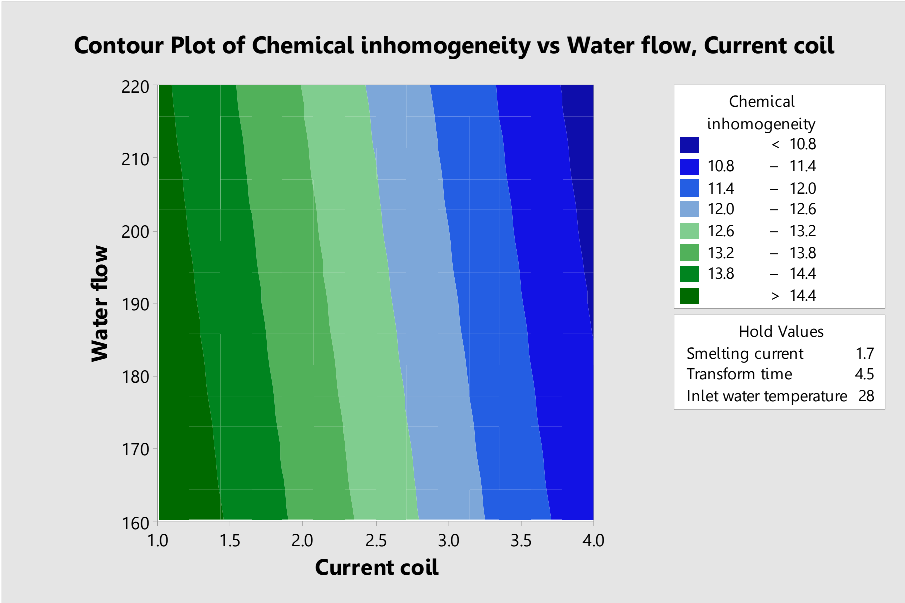

Figure 15. Contour Plot of Water Flow and Current Coil in Chemical Inhomogeneity.

Figure 15 shows that Water Flow and Current Coil are directly proportional. Increasing the Current Coil and Water Flow reduces Chemical Inhomogeneity. Still, the relationship is linear and nearly vertical, indicating that Water Flow has a much smaller impact on Chemical Inhomogeneity than Current Coil. The color blocks in the figure suggest that chemical inhomogeneity decreases as the color approaches dark blue, whereas it increases as the color approaches dark green. The optimal position is near dark blue. The three figures above illustrate the relationship between adjustments to production parameters and the Current Coil. They also demonstrate the relationship between other production parameters and the Current Coil. Except for Inlet Water Temperature, all other parameters are directly proportional to Current Coil, but the slopes of the linear relationships differ. Companies can choose production parameter adjustment methods based on chemical inhomogeneity requirements and the specific color blocks used.

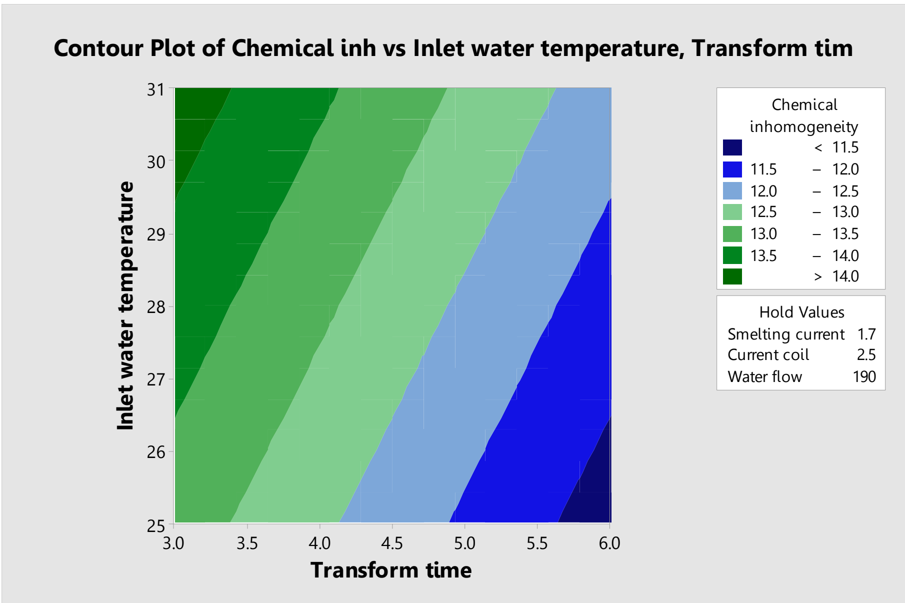

Figure 16. Contour Plot for Inlet Water Temperature and Transformation Time on Chemical Inhomogeneity.

Figure 16 shows that the relationship between inlet water temperature and transformation time is inversely proportional. Increasing transformation time and decreasing inlet water temperature reduce chemical inhomogeneity. The color blocks in the figure indicate that chemical inhomogeneity decreases as the color approaches dark blue and increases as the color approaches dark green. The optimal position is near dark blue.

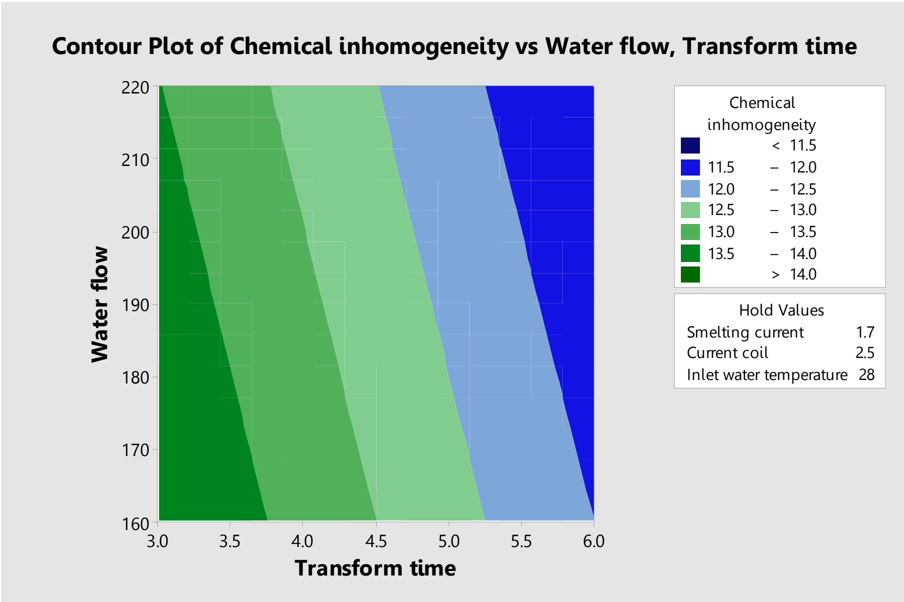

Figure 17. Contour Plot of Water Flow and Transformation Time as a Function of Chemical Inhomogeneity.

Figure 17 shows that Water Flow and Transformation Time are inversely proportional. Increasing Transformation Time and Water Flow reduces Chemical Inhomogeneity. The color blocks in the figure indicate that the closer to dark blue, the lower the Chemical Inhomogeneity, the closer to dark green, the higher the Chemical Inhomogeneity, with the optimal value near dark blue. The two figures above demonstrate the relationship between adjustments to production parameters and Transformation Time. They also illustrate the relationship between other production parameters and Transformation Time. Transformation Time is inversely proportional to Inlet Water Temperature and directly proportional to Water Flow. Analysis of the slopes of these linear relationships indicates that these parameters have essentially the same influence. Companies can select production parameter adjustment methods based on chemical inhomogeneity requirements and specific color blocks. Figure 18 shows that Water Flow and Inlet Water Temperature are inversely proportional. Increasing Water Flow and decreasing Inlet Water Temperature reduce Chemical Inhomogeneity. The color blocks in the figure indicate that chemical inhomogeneity decreases as the color approaches dark blue and increases as the color approaches dark green. The optimal value is near dark blue. The figure above illustrates the relationship between adjustments to production parameters and Inlet Water Temperature. It also demonstrates the relationship between other production parameters and Inlet Water Temperature, which is inversely proportional to Water Flow. Analysis of the slopes of these linear relationships indicates that these parameters have essentially the same influence. Companies can choose production parameter adjustment methods based on chemical inhomogeneity requirements and specific color blocks. As shown in the figures above, the contour map of the Ti-45Nb titanium alloy production conditions clearly illustrates the relationship between the model's production process parameters and the product's chemical heterogeneity. The influence of different parameters on the product and on each other can be observed more intuitively. The trend of product chemical heterogeneity with respect to production process parameters under the corresponding conditions can also be examined for any parameter in the figure, providing a comprehensive foundation and subsequent ideas for related titanium alloy research, as well as detailed parameters and production guidance for other titanium alloy enterprises.

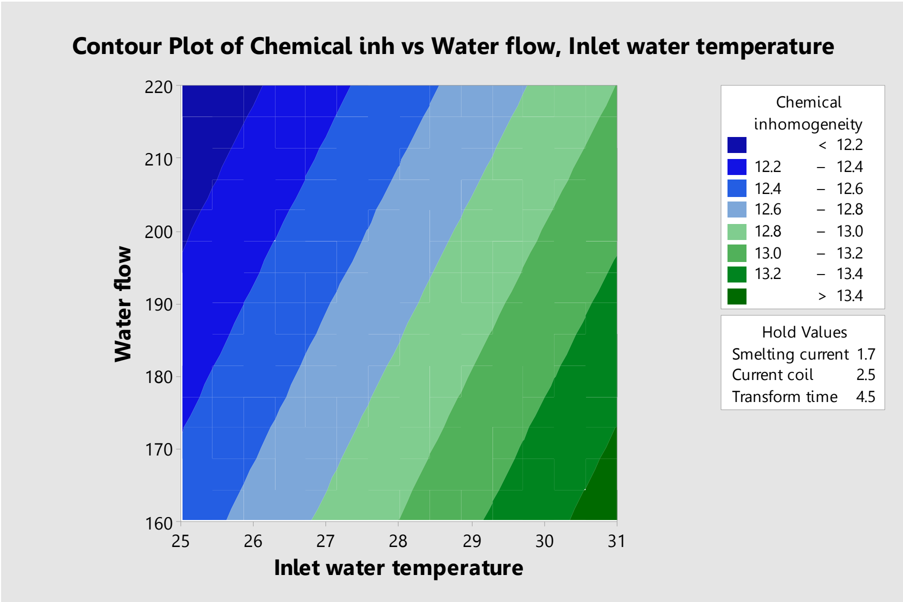

Figure 18. Contour Plot of Water Flow and Inlet Water Temperature with Respect to Chemical Inhomogeneity.

4. Conclusions

The residual plot analysis indicated that the data from the 2^k full factorial experimental design in the DOE were accurate and suitable for analysis, underscoring the applicability of this design for analyzing and optimizing Ti-45Nb titanium alloy production experiments. At a significance level of $\alpha = 0.05$, the model explains nearly all the total variation, indicating effectiveness; the sum of squares of error and mean square error are small, indicating that the experimental design and model fitting are accurate. Response Optimizer analysis shows that after optimizing target yield, the optimal values of the main factors are as follows: Smelting current (KA) = 1.7, Current coil (A) = 3.2542, Transform time (S) = 6, Inlet water temperature (°C) = 25, and Water flow (L/min) = 220. Under these conditions, the chemical inhomogeneity of the produced Ti-45Nb titanium alloy is theoretically 10%. Manufacturers can use the results of this study, along with yield targets, to determine optimal operating conditions and optimize the production process for the Ti-45Nb alloy.

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References

[1] Gosavi, S.; Gosavi, S.; Alla, R. Titanium: A Miracle Metal in Dentistry. *Trends Biomater. Artif. Organs* **2013**, *27*(1), 42–46.

[2] Peters, M.; Kumpfert, J.; Ward, C. H.; Leyens, C. Titanium Alloys for Aerospace Applications. *Adv. Eng. Mater.* **2003**, *5*(6), 419–427. https://doi.org/10.1002/adem.200310095

[3] Kumpfert, J.; Leyens, C. Orthorhombic Titanium Aluminides: Intermetallics with Improved Damage Tolerance. In *Titanium and Titanium Alloys: Fundamentals and Applications*; Leyens, C., Peters, M., Eds.; Wiley-VCH: Weinheim, Germany, **2003**; pp 59–88. https://doi.org/10.1002/3527602119.ch3

[4] Luo, Y. Biotribology. In *Biotribology*; Davim, J. P., Ed.; ISTE-Wiley: London, **2010**; p 157.

[5] Ribeiro, M. V.; Moreira, M. R.; Ferreira, J. R. Optimization of Titanium Alloy (6Al–4V) Machining. *J. Mater. Process. Technol.* **2003**, *143*, 458–463. https://doi.org/10.1016/S0924-0136(03)00457-6

[6] Rahman, M.; Wang, Z. G.; Wong, Y. S. A Review on High-Speed Machining of Titanium Alloys. *JSME Int. J., Ser. C* **2006**, *49*(1), 11–20. https://doi.org/10.1299/jsmec.49.11

[7] Donachie, M. J. *Titanium: A Technical Guide*, 2nd ed.; ASM International: Materials Park, OH, **2000**.

[8] Veiga, C.; Davim, J. P.; Loureiro, A. J. Properties and Applications of Titanium Alloys: A Brief Review. *Rev. Adv. Mater. Sci.* **2012**, *32*(2), 133–148.

[9] Sverdrup, H. U.; Sverdrup, A. E. An Assessment of the Global Supply, Recycling, Stocks in Use and Market Price for Titanium Using the WORLD7 Model. *Sustain. Horizons* **2023**, *7*, 100067. https://doi.org/10.1016/j.horiz.2023.100067

[10] Hu, N.; Xie, L.; Liao, Q.; Gao, A.; Zheng, Y.; Pan, H.; Tong, L.; Yang, D.; Gao, N.; Starink, M. J.; Chu, P. K. A More Defective Substrate Leads to a Less Defective Passive Layer: Enhancing the Mechanical Strength, Corrosion Resistance and Anti-Inflammatory Response of the Low-Modulus Ti-45Nb Alloy by Grain Refinement. *Acta Biomater.* **2021**, *126*, 524–536. https://doi.org/10.1016/j.actbio.2021.02.045

[11] Zhang, L. C.; Chen, L. Y. A Review on Biomedical Titanium Alloys: Recent Progress and Prospect. *Adv. Eng. Mater.* **2019**, *21*(4), 1801215. https://doi.org/10.1002/adem.201801215

[12] Gepreel, M. A.; Niinomi, M. Biocompatibility of Ti-Alloys for Long-Term Implantation. *J. Mech. Behav. Biomed. Mater.* **2013**, *20*, 407–415. https://doi.org/10.1016/j.jmbbm.2012.11.014

[13] Niinomi, M. Recent Research and Development in Titanium Alloys for Biomedical Applications and Healthcare Goods. *Sci. Technol. Adv. Mater.* **2003**, *4*(5), 445–454. https://doi.org/10.1016/j.stam.2003.09.002

[14] *Titanium and Titanium Alloys: Fundamentals and Applications*; Leyens, C., Peters, M., Eds.; Wiley-VCH: Weinheim, Germany, **2003**. https://onlinelibrary.wiley.com/doi/book/10.1002/3527602119 (accessed 2022-09-26).

[15] Li, Y.; Yang, C.; Zhao, H.; Qu, S.; Li, X.; Li, Y. New Developments of Ti-Based Alloys for Biomedical Applications. *Materials* **2014**, *7*(3), 1709–1800. https://doi.org/10.3390/ma7031709

[16] Patel, D.; Kim, S. H.; Qiu, W.; Maeda, M.; Matsumoto, A.; Nishijima, G.; Kumakura, H.; Choi, S.; Kim, J. H. Niobium-Titanium (Nb-Ti) Superconducting Joints for Persistent-Mode Operation. *Sci. Rep.* **2019**, *9*(1), 14287. https://doi.org/10.1038/s41598-019-50549-7

[17] El Khalloufi, M.; Drevelle, O.; Soucy, G. Titanium: An Overview of Resources and Production Methods. *Minerals* **2021**, *11*(12), 1425. https://doi.org/10.3390/min11121425

[18] Durakovic, B. Design of Experiments Application, Concepts, Examples: State of the Art. *Period. Eng. Nat. Sci.* **2017**, *5*(3), 421–439. https://doi.org/10.21533/pen.v5i3.145

[19] Sreela-or, C.; Tharungsri, P.; Yamkong, S.; Kotam, P.; Jaipong, P. Optimum Conditions of Using Bio-Extract from Urine with Vinasse and Manure Affecting Yields of Marigold. *Life Sci. Environ. J.* **2022**, *23*(2), 283–296 (in Thai). https://doi.org/10.14456/lsej.2022.22

[20] Sonsiri, A.; Palicamin, P.; Amdee, N. Development of Plastic Green Composite for Vacuum Mold Process. *FEAT J. Farm Eng. Autom. Technol. J.* **2021**, *7*(1), 1–9 (in Thai). https://doi.org/10.14456/lsej.2024.25