Optimization of Molten Salt Cleaning Process for Surface Roughness of Remanufactured 27SiMn Hydraulic Support Column

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(Received 4 September 2019; revised 28 October 2019; accepted 20 April 2020)

Abstract: During molten salt cleaning of remanufactured 27SiMn hydraulic support column, oxidation occurs on the surface of metal substrate. This results in a change of the surface roughness of metal substrate after cleaning, which affects subsequent remanufacturing process. To decrease the effect is very important. This paper analyzed the oxidation mechanism of molten salt cleaning, explored the oxidation reaction that occurred during cleaning, and determined the key process parameters of cleaning that affecting oxidation reaction. By using central composite experimental design method and taking surface roughness variation of 27SiMn steel samples before and after molten salt cleaning as response variable to optimize the key process parameters, the optimal parameters of molten salt for cleaning remanufactured 27SiMn hydraulic support column could be obtained. The results show that the oxidation reaction of cleaning paint dirt can protect metal substrate from oxidation to a certain extent, and cleaning temperature and placement depth of metal substrate have a direct impact on the degree of oxidation reaction. When the cleaning temperature is 300 ℃ and the distance between paint dirt and free surface of molten salt is 0.5 times the height of the parts, the surface roughness variation is minimal. Therefore, the cleaning quality will be improved under such parameters.

Key words: surface roughness; molten salt cleaning; hydraulic support column; central composite experimental design; remanufacturing

CLC number: TG154 **Document code:** A **Article ID:** 1005-1120(2020)03-0460-07

0 Introduction

As an extension of equipment manufacturing industry chain, remanufacturing is one of the most effective ways to make resource recycled[1]. Hydraulic support is the key system to make sure safety in underground coal mining process[2]. Hydraulic support column, as shown in Fig.1, is the main bearing part of hydraulic support, which can bear and transmit the main load from the roof of fully mechanized mining face. Due to long-term use in harsh environment of acid and alkali corrosion, hydraulic support column is subject to corrosion, wear, impact and other comprehensive effects, resulting in the peeling of surface paint, and damage of substrate[3]. This will cause equipment failure and affect the whole coal mining process. Therefore, remanufacturing of hydraulic support column is an inevitable trend for the sustainable use of mining machinery[4]. It is the first step in remanufacturing process to do a good job of

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How to cite this article: XIN Benli, SUN Yihang, JIA Xiujie, et al. Optimization of molten salt cleaning process for surface roughness of remanufactured 27SiMn hydraulic support column[J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2020, 37(3): 460-466.

http://dx.doi.org/10.16356/j.1005-1120.2020.03.012

cleaning paint dirt on hydraulic support column. Cleaning quality directly affects subsequent remanufacturing. Molten salt cleaning is an efficient industrial cleaning method which uses molten salt as the cleaning medium. It combines physical and chemical action to clean carbon, paint, oil and other typical dirt[5-7]. Because of low energy consumption and little pollution, this method has been gradually applied in cleaning of mining machinery.

Fig.1 Hydraulic support column

Under the premise of high efficiency and environmental protection, the effect of molten salt cleaning on material properties of remanufactured hydraulic support column determines whether it meets requirements of subsequent remanufacturing. In recent years, domestic and foreign scholars have explored the effects of molten salt cleaning on various properties of iron-based alloy materials commonly used in mining machinery[8-10], including surface roughness, hardness and tensile strength, etc. The results show that molten salt cleaning has little effect on hardness and tensile strength of iron-based alloy materials, but has a significant effect on surface roughness. The reason is that oxidation reaction occurs continuously in the process of molten salt cleaning, which leads to surface oxidation of metal substrate[11-13]. The resulting oxide layer has a great effect on the surface roughness. Surface roughness is closely related to wear resistance, fatigue strength, contact stiffness, vibration and noise of mechanical parts, which has an important impact on service life and reliability of mechanical products[14]. Therefore, optimizing the molten salt cleaning process to reduce the influence on surface roughness is of great significance to ensure its remanufacturing quality and improve its service life.

In this paper, 27SiMn steel used for manufacturing hydraulic support column was selected for the optimization experiment of molten salt cleaning process. By adopting central composite experimental design method, and using surface roughness variation of metal before and after molten salt cleaning as response value, the process parameters of molten salt cleaning were optimized. In the end, the optimal parameters, which realized efficient and high-quality cleaning of paint dirt on 27SiMn hydraulic support column, were obtained.

1 Experimental Design of Molten Salt Cleaning

1.1 Oxidation analysis of molten salt cleaning

Oxidation is the main action for molten salt removing paint[15-16]. The formula of molten salt used in this study is composed by KNO_3-$NaNO_3$-$NaOH$. Ion detection of the used molten salt showed that it contained a large amount of CO_3^{2-}, but the content of OH^- was greatly reduced. Analysis of gas products revealed that no acidic nitrogen oxide gas was found, which was due to the absorption of NaOH in cleaning process.

The specific reaction equations of molten salt in cleaning paint dirt were

$$2C_aH_b + (2a + b/2)O_2 \rightarrow 2aCO_2 + bH_2O \quad (1)$$

$$C_aH_bN_c + O_2 \rightarrow CO_2 + H_2O + N_2 + NO_x \quad (2)$$

$$CO_2 + 2OH^- \rightarrow CO_3^{2-} + H_2O \quad (3)$$

$$4NO_x + (5 - 2x)O_2 + 4OH^- \rightarrow 4NO_3^- + 2H_2O \quad (4)$$

In molten salt cleaning process, the substrate of iron-based alloy materials was also oxidized. On one hand, Fe element reacted with molten NaOH to form Fe_3O_4; on the other hand, high temperature cleaning conditions catalyzed the oxidation of Fe element in aerobic environment. With the removal process of paint dirt, metal substrate was inevitably oxidized in molten salt medium, resulting in the change of surface roughness after cleaning. Studies have shown that both the oxidation of paint dirt removal process and the oxidation of metal substrate consume a large amount of NaOH, while the content of NaOH in the mixed molten salt system is limited. So, the oxidation reaction of paint dirt removal process can protect metal substrate from oxidation to a certain extent. Speeding up the reaction rate of paint dirt removal can shorten the cleaning time, which will reduce the contact time between metal substrate and molten salt, thus reducing the oxidation of substrate.

As the key condition of oxidation, cleaning temperature directly affects the degree of each oxidation reaction in molten salt cleaning process. And the amount of oxygen dissolved in molten salt is different at different depths, which also affects the reaction. Selecting proper cleaning temperature and placement depth can reduce the oxidation of metal substrate and the change of surface roughness while completely removing the paint dirt. This can effectively reduce the effect of molten salt cleaning on the properties of iron-based alloy materials and improve the cleaning quality.

1.2 Experimental materials and equipment

27SiMn steel, as an iron-based alloy material, is commonly used for engineering machinery. It is often used in manufacturing of hydraulic support column[17]. Its element composition and content are shown in Table 1.

Table 1 Elemental composition and content of 27SiMn steel

Element	C	Si	Mn	S	P	Cr	Mo
Content/%	0.24—0.32	1.10—1.40	1.10—1.40	⩽0.035	⩽0.035	⩽0.25	⩽0.15

In this paper, 27SiMn steel was selected as the research object, and the material was processed into 13 cylindrical samples with a diameter of 20 mm and a height of 10 mm. The samples were treated to make the surface condition similar to that of the hydraulic support column, as shown in Fig.2.

Fig.2 Experimental samples before painting

Surface roughness of the 13 samples was test. Each sample was tested three times, and the average value was taken as initial value. After surface roughness test, the samples were painted. The main components of the paint were the same as those used on hydraulic support column. The thickness of paint sprayed on the samples was 0.05 (±0.005) mm. After painting, the samples were dried in a ventilated environment to meet experimental standard. The experimental samples after painting were shown in Fig.3.

In this experiment, a molten salt cleaning equipment which can control temperature was used to clean the samples. The main body of the equipment consists of a cleaning tank, a heating and holding furnace and a temperature control box to achieve precise temperature control. The surface roughness test used Wyko NT9300 white light interferometer with high measurement accuracy.

Fig.3 Experimental samples after painting

1.3 Experimental program

This experiment intended to optimize the cleaning temperature and the placement depth of painted samples. Surface roughness variation of the samples before and after molten salt cleaning was taken as response variable. Two-level full-factor experiment was carried out by using central composite experimental design commonly used in response surface methodology. The total number of experiments was 13. The range of the cleaning temperature was 270—360 ℃ and the distance was 5—65 mm (0.5—6.5 times the height of the sample). Level setting of experimental factors was shown in Table 2.

Table 2 Level setting of experimental factors

Factor	Low level	High level
Temperature/℃	270	360
Distance/mm	5	65

The experimental steps for molten salt cleaning were as follows:

(1) A sufficient amount of the mixed salt that

consisting of KNO_3-$NaNO_3$-NaOH was poured into the cleaning tank to fully melt.

(2) The experimental samples after painting were subjected to molten salt cleaning under 13 sets of specific temperature and distance.

(3) When the paint dirt was completely removed, the samples were taken out. Then the residual molten salt on the samples was removed by using an ultrasonic cleaner. After that, the samples were dried.

(4) The surface roughness of each cleaned sample was tested and compared with the initial value tested before. By subtracting the initial value from the final value, the surface roughness variation was then calculated and denoted by ΔRa. The central composite experimental design and corresponding results were shown in Table 3.

Table 3 Central composite experimental design and corresponding results

Running order	Temperature/℃	Distance/mm	ΔRa/nm
1	270.0	35.0	22.44
2	315.0	35.0	−46.57
3	283.2	13.8	13.62
4	346.8	56.2	−137.49
5	315.0	5.0	−13.80
6	315.0	35.0	−57.63
7	315.0	65.0	−104.62
8	315.0	35.0	−33.27
9	315.0	35.0	−39.29
10	315.0	35.0	−47.19
11	283.2	56.2	−49.43
12	346.8	13.8	−81.26
13	360.0	35.0	−100.26

2 Response Surface Optimization of Molten Salt Cleaning Process

2.1 Fitting of regression equation

(1) Regression analysis

Based on the central composite experimental design, the surface roughness variation of 27SiMn steel samples under various temperature and distance was investigated. A corresponding quadratic regression model was established by coding and analyzing the two factors. The coded estimated regression coefficients in the quadratic regression model were listed in Table 4, where SE coef. is the standard error for coefficients, and Temp is the abbreviation of temperature.

Table 4 Estimated regression coefficients for ΔRa

Term	Coef. value	SE coef.	*T* ratio test	*P*-value
Constant	−44.79	4.73	−9.47	0.000
Temp	−44.56	3.74	−11.91	0.000
Distance	−30.96	3.74	−8.28	0.000
Temp*Temp	−0.71	4.01	−0.18	0.865
Distance*Distance	−10.85	4.01	−2.71	0.030
Temp*Distance	1.71	5.29	0.32	0.757

As demonstrated in Table 4, the corresponding *P*-values of temperature and distance in linear terms were both 0.000, which was much smaller than 0.05. This indicated that they were significant. The corresponding *P*-value of distance*distance in square terms was 0.030, also smaller than 0.05. However, the corresponding *P*-value of temperature*temperature in square terms was 0.865 and the corresponding *P*-value of temperature*distance in interaction term was 0.757. Both of them were much greater than 0.05, which indicated that these insignificant terms should be deleted from the quadratic regression model. The estimated regression coefficients after correction were listed in Table 5. From Table 5, we could see the *P*-values for linear and square regression terms were all less than 0.05, which meant they were all statistically significant.

Table 5 Estimated regression coefficients for ΔRa after correction

Term	Coef. value	SE coef.	*T* ratio test	*P*-value
Constant	−45.28	3.40	−13.31	0.000
Temp	−44.56	3.33	−13.38	0.000
Distance	−30.96	3.33	−9.30	0.000
Distance*Distance	−10.76	3.54	−3.04	0.014

(2) Variance analysis

Variance analysis for the surface roughness variation was carried out, and the specific data were shown in Table 6, where DF is the degree of freedom, Adj.SS is the adjusted sum of squares of deviation from mean, and Adj.MS is the adjusted mean square. The adjusted R-Sq value, which was reasonably identical to the R-Sq value, indicated that extra variables were not included in the model. Furthermore, the P-value for lack of fit was 0.478, which was much larger than 0.05. This indicated that the data model does not have any lack of fit.

Table 6 Variance analysis for Δ*Ra*(R-Sq=96.83%, R-Sq (adj)=95.77%)

Source	DF	Adj. SS	Adj. MS	F ratio test	P-value
Model	3	24 373.7	8 124.6	91.57	0.000
Linear	2	23 553.9	11 777.0	132.73	0.000
Temp	1	15 883.3	15 883.3	179.01	0.000
Distance	1	7 670.6	7 670.6	86.45	0.000
Square	1	819.8	819.8	9.24	0.014
Distance*Distance	1	819.8	819.8	9.24	0.014
Error	9	798.6	88.7		
Lack-of-fit	5	461.8	92.4	1.10	0.478
Pure error	4	336.8	84.2		
Total	12	25 172.3			

The coefficients of regression equation for the surface roughness variation of 27SiMn steel samples were shown in Table 7.

Table 7 Coefficients of regression equation for Δ*Ra*(Uncoded unit)

Term	Coef. value
Constant	417.6
Temp	−1.400
Distance	0.215
Distance*Distance	−0.023 92

(3) Residual analysis

Based on the residual condition, fitting effect of the model could be diagnosed by analyzing the reliability, periodicity and interference of the data. The residual plots of the surface roughness variation were shown in Fig.4.

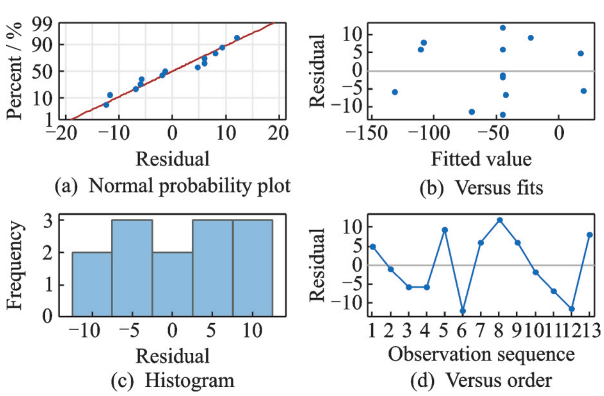

Fig.4 Residual plots of Δ*Ra*

As can be seen from the analysis of Fig.4 above, the residual values were normally distributed, and the scatter points were randomly distributed above and below horizontal axis. These indicated that the residual was not abnormal.

(4) Establishment of regression equation

By regression analysis, variance analysis and residual analysis, the regression equation for the surface roughness variation was obtained as

$$\Delta Ra = 417.6 - 1.400T + 0.215D - 0.023\,92D^2 + \xi \tag{5}$$

where ΔRa stands for the surface roughness variation of 27SiMn steel samples before and after molten salt cleaning, T for the cleaning temperature, D for the distance between paint dirt on the samples and free surface of the molten salt, and ξ for the regression error.

2.2 Response surface analysis and target optimization

(1) Contour plot and response surface plot analysis

Contour plot and response surface plot based on the fitting model were shown in Fig.5 and Fig.6. And the trend of ΔRa vs. temperature and distance could be observed in conjunction with these two figures.

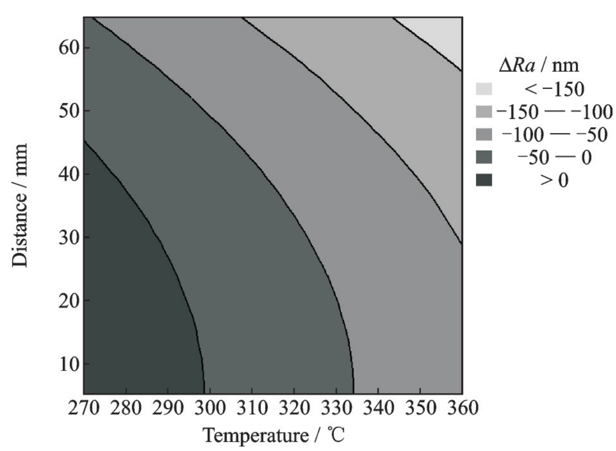

Fig.5 Contour plot of Δ*Ra* vs. temperature and distance

(2) Target optimization of Δ*Ra*

The response optimizer was used to optimize target value. The optimization target was to make ΔRa equal to 0, which meant that the cleaning process had minimal effect on the surface roughness. According to the response optimization results in

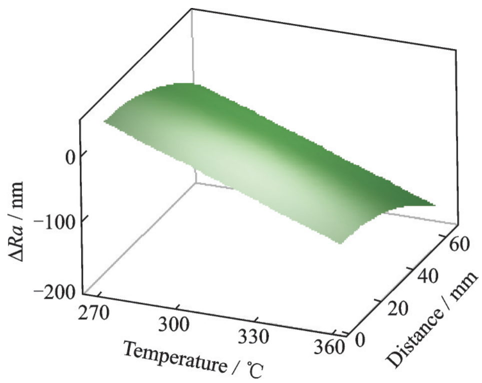

Fig.6 Surface plot of ΔRa vs. temperature and distance

Fig.7, when the temperature was about 300 ℃ and the distance was 5 mm, i.e. 0.5 times the height of the sample, the response value was optimal.

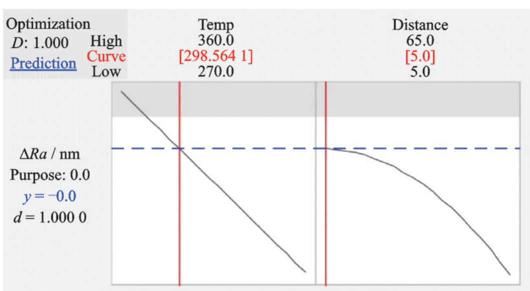

Fig.7 Response optimization plot of ΔRa

3 Conclusions

(1) Molten salt can effectively remove the paint dirt on hydraulic support column by oxidation. The iron-based substrate is also easy to be oxidized to Fe_3O_4, which will make the surface roughness of cleaned substrate changed. However, the oxidation reaction for paint removing will restrict the oxidation to substrate. In order to minimize the substrate oxidation, an optimal experiment was designed to explore the effect of cleaning parameters. Research shows that the cleaning temperature and the placement depth of metal substrate are the main factors for the degree of oxidation reaction.

(2) In this paper, the cleaning temperature and the distance between paint dirt on the samples and free surface of molten salt were optimized by using experimental design method of central composite and surface roughness variation of 27SiMn steel samples as response variable. With ΔRa tending to zero as the optimization target, the optimal process parameters of molten salt for cleaning remanufactured 27SiMn hydraulic support column were finally obtained. Results show that when the cleaning temperature is 300 ℃ and the distance between paint dirt and free surface of molten salt is 0.5 times the height of the parts, the optimization target is achieved.

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Acknowledgement This work was supported by the National Natural Science Foundation of China (No.51375278).

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Author contributions Mr. **XIN Benli** designed the study, conducted the analysis, interpreted the results and wrote the manuscript. Mr. **SUN Yihang** contributed to data for experimental analysis. Prof. **JIA Xiujie** contributed to the ideas and methods for the experiment. Prof. **LI Fangyi** contributed to the discussion and background of the study. Dr. **WANG Xing** contributed to the research on the mechanism of cleaning. Mr. **XIONG Sheng** contributed to the study of chemical reactions. Mr. **MA Mingliang** contributed to the discussion of the results. Mr. **ZHANG Baocai** contributed to the polishing of the content. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: ZHANG Huangqun)

针对再制造27SiMn钢液压支架立柱表面粗糙度的熔盐清洗工艺优化

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摘要:在对再制造27SiMn钢液压支架立柱的熔盐清洗过程中,金属基体表面发生氧化,导致清洗后工件表面粗糙度参数发生改变,影响后续再制造工序。为最大限度降低该影响,通过分析熔盐清洗氧化作用机理,探究清洗过程中发生的氧化反应,确定影响氧化反应进行的关键清洗工艺参数。采用中心复合试验设计方法,以熔盐清洗前后27SiMn钢材料样件表面粗糙度变化量为响应变量,对关键清洗工艺参数进行优化,最终获得用于清洗再制造27SiMn钢液压支架立柱表面油漆污物的最优熔盐清洗工艺参数。结果表明,熔盐清洗去除油漆污物过程的氧化反应能在一定程度上限制金属基体发生的氧化反应,而清洗温度及清洗放置深度对氧化反应程度产生直接影响。当清洗温度为300 ℃、样件喷漆面与熔盐自由液面间距离为0.5倍的样件高度时,表面粗糙度变化量最小,该参数下清洗质量最优。

关键词:表面粗糙度;熔盐清洗;液压支架立柱;中心复合试验设计;再制造