Carbon deposition mechanism of molten salt cleaning and optimization of multicomponent molten salt formula for remanufacturing

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Abstract
In remanufacturing engineering, cleaning is the key factor for subsequent blank inspection and parts repair. Molten salt has the characteristics of low viscosity, good fluidity, and strong chemical stability. Salt bath cleaning can be comprehensively applied to remove various organic pollutants. Molten salt has the function of self-cleaning. The dirt in the cleaning pool can be decomposed and reused. Moreover, the waste molten salt is massive, and the waste residue is easy to treat. The formation and adsorption mechanism of carbon deposition was explored, and the formation mechanism of carbon deposition was verified by experiments. Then, the existing formula was improved by mixing experiment and compared with the current cleaning method; the cleaning effect was excellent. A new molten salt formula is proposed on the basis of the research on solar thermal storage medium. The composition percentage and the optimal process parameters of the new molten salt formula were determined on the basis of the experimental design of mixture. The cleaning effect of the new formula is good.

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Keywords
Remanufacturing engineering, cleaner production, molten salt cleaning, molten salt formula, carbon deposition

Introduction
Remanufacturing engineering is an emerging industry to solve the problems of the current resource shortage, to reduce energy consumption, and to achieve sustainable development.\textsuperscript{1–3} With the continuous improvement of the remanufactured product performance and the deepening of the remanufacturing concept, remanufactured products play an important role in the field of green products.\textsuperscript{4–6} Cleaning is an indispensable craft in the remanufacturing process, and the surface cleanliness of remanufactured parts is related to subsequent detection, repair, processing, and assembly.\textsuperscript{7,8} Remanufacturing blank surface cleanliness can affect the discovery of microcrack as well as the qualitative and judgment of the damage degree during the testing phase. In the repair process, the phenomenon of porosity and sand inclusion is found in the interface between the base and the repair layer because of the residual contaminant, leading to the reduction of bonding strength. In addition, the thermal effect of pollutants can decrease machining accuracy.\textsuperscript{9,10} The high standard of cleanliness helps to find various hidden dangers, reduce processing of defects caused by pollutants exposed in the subsequent process, and improve the process flow and technology of the remanufacturing cleaning process, which is an important part of the green economy that reflects the whole life cycle of remanufacturing products.\textsuperscript{11,12}

The Kolene company in the United States has been using the complete set of equipment for cleaning since 1980. However, due to the confidentiality of corporate information, no specific process or parameters are available for reference. In 2014, Professor Li J of Texas established a mathematical model between the composition of molten salt and the temperature; he studied the damage caused by molten salt.\textsuperscript{13–15} However, no breakthrough was achieved in the field of molten salt composition. In addition, the temperature of the molten salt washing above 400°C causes the decomposition of nitrate, producing more harmful gases. The high temperatures are likely to cause remanufacturing blank surface oxidation in the cleaning process, affect the use of the subsequent, and increase the precision of the energy consumption.

Wang Yongkai introduced the clean molten salt method and designed two different types of devices for industrial production. The matrix damage experiments using molten salt wash showed no hardness and deformation of substrate basic in the molten salt washing at 400°C. The molten salt washing for aluminum alloy matrix has serious corrosion phenomena in corrosion detection. To reduce corrosion, the method of lower temperature and lower content of sodium hydroxide could be adopted. Optimizing the formula NaNO\textsubscript{3} and the proportion of NaOH
could reduce the cost. However, the molten salt is decomposed during use, producing a large number of toxic and harmful gases. Hou Fuxiang conducted experiments on engine carbon deposition in molten salt cleaning, proposed the hypothesis of the basic mechanism of carbon deposition removal, optimized the experimental formula of molten salt cleaning by 0.618 methods, and pointed out the advantage of cleaning time of only 7 min.\textsuperscript{16} The formula only included proportion optimization instead of the fundamental breakthrough. The formation mechanism of pollutants was not explained. Thus, the improvement was limited to the change in formula ratio guided by temperature and cleaning time because no theoretical support was provided for the improvement of the formula and process. Ge Shunxin focused on the improvement of the molten salt cleaning formula, changing the composition of molten salt to the combination of NaOH, NaNO\textsubscript{2}, and KNO\textsubscript{3}. He proved that the new formula was used to reduce the melting boiling point and the liquid viscosity by analyzing the thermo–physical properties of the formula. However, he did not perform experiments for practical application. NieYanYan proposed molten salt washing method on the basis of the improved formula. The experiment proved that molten salt above 400°C could clean up the carbon deposition on the surface of the valve within 2–5 min. The new formula of molten salt cleaning could only play an auxiliary role in the removal of scale and rust, and the subsequent pickling was required to play a major role; but it would significantly reduce the pickling time. Explaining how the improved formulation ratio applies to pollutants is impossible because the dissociation of pollutants has not been systematically studied. In addition, the decomposition of sodium nitrate starts at 380°C, thereby producing a large number of harmful NOx gases. The temperature of 400°C is still too high for cleaning; thus, it needs to be reduced.\textsuperscript{17,18}

However, the influencing factors and some key issues of the removal mechanism in the multicomponent molten salt cleaning were not studied further in the previous literature. Thus, on the basis of the current situation of molten salt cleaning, experiments on carbon deposition in molten salt cleaning with different KNO\textsubscript{3}–NaNO\textsubscript{2} formula components were conducted, and the influence of formula, temperature, and time factors on the cleaning effect was explored. The aim is to reveal the influence of various factors on molten salt cleaning and its removal mechanism to provide theoretical support for the widespread use of molten salt cleaning technology in the remanufacturing industry.

**Analysis of the formation mechanism of carbon deposition**

*Chemical reaction in the formation process of carbon deposition*

Carbon accumulation in the engine mainly results from the incomplete combustion of fuel oil and the incomplete combustion of residual lubricating oil. When the oxygen supply of the engine is insufficient, the lubricating oil and fuel oil in the engine cannot be fully burned, resulting in the initial accumulation of carbon molecule particles. The internal temperature of the diesel engine cylinder reaches 300°C–500°C, and the instantaneous temperature in the cylinder can reach 1500°C–
1800°C after ignition. When working, the pressure in the cylinder can reach 20–200 MPa. Small molecules of fuel oil and lubricating oil under high temperature and high-pressure cylinder environment undergo oxidation reaction, generating various substances, such as alcohols, aldehydes, ketones, and acids, among which some substances continue to react and undergo addition polymerization and condensation reaction.19–21

Under such high temperature and pressure, the following reactions occur:22]

\[
R_1CH_3 + O_2 \xrightarrow{600^\circ C \ \text{high pressure}} R_1COH + H_2O (1-1)
\]

\[
R_1COH + O_2 \rightarrow R_1COOH + H_2O (1-2)
\]

\[
R_2CH_3 + O_2 \xrightarrow{\text{Metal catalyst}} R_2CH_2OH (1-3)
\]

\[
R_1COOH + R_2CH_2OH \rightarrow R_1COOCH_2R_2 (1-4)
\]

In the above formula, \(R_1\) and \(R_2\) represent the remaining alkanes on the C chain. \(R_1COH, R_1COOH, R_1COOCH_2, \) and \(R_2CH_2OH\) are consistent with the substances obtained by infrared scopy. This finding indicates that the chemical reactions occurred, proving that carbon deposition is composed of a large number of organic molecules.

**Adsorption mechanism of carbon deposition**

In the early stage of assembly and use of engine, antirust oil is sprayed on the surface, and a layer of organic matter is adsorbed on the surface of the matrix after a few minutes to form a conditional film. Subsequently, the generated large carbon deposition particles and metal particles constantly adhere to the surface film. At the initial stage, due to the small surface area of carbon, the gelatinous layer is relatively thin, and the carbon deposition particles easily fall off. In addition, adhesion is a reversible process, and the carbon molecules find a suitable adhesion group on the surface of the conditional membrane, and then become permanent adsorption. Incomplete combustion fuels and lubricants are also continuously filled into the carbon particles, producing colloid-like properties and forming a 3D structure.22–25 The loose 3D structure forms a large number of irregular holes. Thus, the newly formed carbon deposition particles constantly adhere to each other, the carbon deposition area constantly expands, and the thickness constantly increases, as shown in Figure 1.

When the engine is working normally, small metal particles are produced by abrasion. These particles act as catalysts to continuously promote the reaction of small molecules, and finally form large molecules through a series of polymerization reactions. Large molecules with large mass adhere to the surface of the cylinder in high-speed motion because the inner surface of the cylinder is not smooth. Thus, the probability of accumulation of carbon macromolecules in the cylinder increases. In the continuous movement, carbon molecules continue to accumulate, gradually
forming a porous gelatinous layer. The gelatinous layer has great viscosity, and its porous structure constantly absorbs the newly generated carbon small molecules, and even some incomplete combustion of lubricating oil and small metal particles. In addition, dust in the air co-deposits on this adhesive layer. Under the environment of high temperature and high pressure, the colloidal layer is constantly compressed, and the pore structure is constantly reduced until it is compressed into the asphaltene layer, forming a carbon deposit with complex components and dense structure.\textsuperscript{26–28}

In previous studies, carbon deposition was mostly regarded as a process of accumulation on a solid surface. In fact, the entire adhesion process is composed of carbon deposition particles, metal particles, full combustion of lubricating oil, and fuel

\textbf{Figure 1.} Model of carbon deposition adhesion.
oil. This process is similar to the glue bonding process. It is an unbalanced thermodynamics and kinetic process driven by various physicochemical processes.

**Formula optimization of multicomponent molten salt**

*Current shortage of molten salt formula*

The optimal cleaning temperature of the previous nitric acid molten salt formula was 330°C–360°C. However, the decomposition point of the main component sodium nitrite is 320°C. The operating temperature is higher than the decomposition point, which causes the nitrite to decompose quickly, thereby producing oxygen, nitrogen oxides, and sodium oxide.

\[ \text{NaNO}_2 \xrightarrow{320 \degree C} \text{O}_2 + \text{NO}_x + \text{Na}_2\text{O} \quad (1-5) \]

Therefore, a large amount of gases, such as NO and NO$_2$, are produced in the process of molten salt cleaning based on the above formula.

1. During the experiment, despite the use of filter masks, people still experienced dizziness and nausea after completing the experiment. Long-term exposure to nitrogen oxides can cause mutations in genetic material and can lead to cancer. The waste gas contains small carbon particles that do not decompose in time. This waste gas can also enter the body through the nose and mouth and deposit in the lungs.

2. The emission of waste gas in industrial production affects the environment. High-temperature industrial waste gas contains a large number of dust particles and a large number of harmful substances. NO$_X$ causes regional environmental damage and affects the ecological environment.

3. Special treatment is required for exhaust gas that does not satisfy China’s emission standards for industrial waste gas. Thus, the cost of remanufactured products increases, thereby opposes the green circular economy advocated by the country.

Therefore, considering that molten salt has heating inertia, 280°C–300°C is the ideal working temperature when molten salt cleaning is applied to actual production.

**Theoretical basis of formula optimization**

The ideal molten salt for cleaning should have a low melting point, and nitrates can decrease the melting point of the salts system compared to other salts. Thus, we selected nitrics to conduct our experiment. In the previous formula of nitric acid molten salt, when the content of sodium nitrite increased from 20% to 80%, differential scanning calorimetry (DSC) experiment shows that no stable interval between 250°C and 400°C for different proportions of molten salt. This finding
indicates that all components in molten salt have changed. The change in composition indicates that the sodium nitrite decomposes and releases harmful gases, as shown in Figure 2.

The mixed molten salts of NaNO₂, NaNO₃, and KNO₃ were studied. Multiple molten salts are suitable for cleaning because of its advantages, such as low melting point, large heat capacity, good fluidity, and stable nature. When mixed molten salt is used with solar energy to store heat, a relatively large specific heat capacity is pursued.³⁰,³¹

When the mixed molten salt of multiple nitric acid is used for cleaning, the molten salt composition should be stabilized during operation. We selected different components of molten salt for DSC experimental analysis, as shown in Table 1.

Figure 3 shows that although the composition of molten salt is different, a section of the curve is relatively stable compared with other parts within the temperature range of 250°C–300°C. The approximate horizontal curve shows that the heat absorbed by molten salt is consistent as unit temperature increases. This finding shows that the molten salt is in a stable state at this temperature, and all the components in the molten salt are in a liquid state, maintaining stable chemical properties.

### Table 1. Melting and boiling points of each component.

|                  | NaNO₂ | NaNO₃  | KNO₃ |
|------------------|-------|--------|------|
| Melting point    | 270   | 306.8  | 334  |
| boiling point    | 320   | 380    | 400  |
| Break points     | 320   | 380    | /    |

Figure 2. DSC diagram of binary mixed nitric acid molten salt.
The reason for this finding is that although the mixed molten salt is dried, water still exists in the air in the cooling process. As shown in Figure 4, the temperature rises to 150°C, the moisture in the mixture is lost; thus, the weight remains almost the same. When the temperature rises to 260°C, the weight begins to decrease slowly because the melting point of the mixed molten salt is approximately 210°C. When the temperature rises to 250°C, the liquid volatilization begins to accelerate. The heat absorption of molten salt is accelerated when the temperature is higher than 320°C. This finding indicates that the composition is changed and the weight loss of molten salt begins to accelerate. Although the weightlessness rate is not very large, large-scale use also causes some waste in the production. Therefore, the

Figure 3. DSC image of mixed molten salt.

Figure 4. Weightlessness experiment of multicomponent molten salt.
temperature should be controlled below 300°C. Increase in temperature reduces the melt salt viscosity and surface tension, which is more conducive to cleaning. In the subsequent experiment, we set the temperature to 300°C given that the thermal properties of multiple molten salts are the same.\textsuperscript{32,33} We study the effect of molten salt with different proportions on the cleaning effect at 300°C.

**Formula optimization of multiple molten salts**

(1) Experimental purpose

At the cleaning time of 2 min and cleaning temperature of 300°C, we aim to determine the ratio of KNO₃, NaNO₂, and NaNO₃ when the optimal removal rate is determined.

(2) Experimental subject

The engine valve stem. The same equipment is used.

(3) Test method and design

The optimal ratios of KNO₃, NaNO₂, and NaNO₃ were designed in this experiment, and a quantitative relationship was found among the three components. The sum of the ratios was 100%. Thus, the orthogonal experimental design and the response surface experimental design could not be applied to this experiment. After screening, a mixing experiment design was selected. In the mixing design, the regression equation of the test index and the percentage of each component in the mixture and its graphic-response surface through the mixing experiment of different percentage components are obtained, and finally a statistical conclusion is provided.

The mixing experiment is applied in the process of industrial and agricultural production and scientific research. At least three types of raw materials are mixed together according to percentage to form a new item. The relationship between the proportion of various components in the mixture and the experimental results is judged by the designed parameter experiment. The condition of the mixing experiment is that the nature of mixing material is only related to the percentage of each component, not to the total amount of mixing material. The composition of each component must be between one and zero, and the sum of the content of each component must be 100%.

As shown in Figure 5, the three components are mixed into the experimental formula according to different proportions. The indexing measurement is completed in accordance with the test requirements. The thin line from the vertex to the edge indicates the trend of the influence of a component on the experimental index.

In accordance with the requirements, the ratio of KNO₃, NaNO₂, and NaNO₃ is set between 0.1 and 0.8, as shown in Table 2.
Some studies have found that when the temperature of molten salt is approximately 300°C, the effect of molten salt on the matrix is very small. Thus, in this test, only the decontaminability of the new molten salt is used as the judgment standard.

\[ a = \frac{m_2 - m_1}{m_3 - m_1} \times 100\% \]  

(1 – 6)

where \(m_1\) represents the mass before cleaning, \(m_2\) represents the mass after cleaning, and \(m_3\) represents the mass after a complete cleaning.

According to the Design Expert software, we select the mixing experiment design and obtain the following Table 3.

(4) Experimental steps and phenomena

According to the given formula, the total amount was 1 kg, and the NaOH content accounted for 30%. The remaining content was weighed in accordance with the proportion given in the experimental design and marked in a sealed bag for use.

The prepared samples were marked, weighed, and recorded before the experiment using a precision balance.

We placed the recipe in a container and heated it to 300°C, and then kept warm. Subsequently, we placed the valve rods in the container in accordance with the marks and cleaned them for 2 min. In the experiment process, the surface of the valve rod initially condensed a layer of a white object, which is preliminarily judged crystal mixed with molten salt. After approximately 10 s, the crystals began to

Figure 5. Experimental schematic of the mixing design.

Table 2. Upper and lower limits of design components in the mixing experiment.

|           | KNO₃ | NaNO₂ | NaNO₃ |
|-----------|------|-------|-------|
| Min       | 0.1  | 0.1   | 0.1   |
| Max       | 0.8  | 0.8   | 0.8   |
dissolve rapidly, and black flocculants started to float on the surface of the molten salt. A black smoke started to form. After 60 s, bubbles appeared in the molten salt continuously, and the reaction was intense.

The valve rod cleaned for 2 min was dried, and the weight recorded at this time was $m_2$. After the measurement was completed, it was placed back into the container until the surface was completely free of contaminants. Then it was removed, air-cooled, cleaned, dried, weighed, and recorded as $m_3$. We removed the molten salt from the container, washed and dried the container, and repeated the steps until all experiments were completed.

(5) Analysis of experimental results

We filled the data obtained from the mixing experiment, calculated the corresponding decontamination percentage, and input the final experiment result in the mixing experiment design table of Design Expert, as shown in Table 4.

**Establish regression models.** According to the Design Expert software, the Quadratic model was selected for correction and analysis of the regression coefficient.

According to mathematical statistics, if the $p$-value is less than 0.001, then the effect on the result is extremely significant; if the $p$-value is greater than 0.001 and less than 0.05, then the effect on the result is significant; if the $p$-value is greater than 0.1, then the effect on the result is insignificant. If these items without significant influence on the results are removed, then they may greatly affect the improvement in the accuracy of the whole model. In the Table 5, $p$ (potassium nitrate $\times$ sodium nitrite) $>0.05$ indicated that this item has insignificant influence on the experiment.

As shown in Table 6, the $F$ value of the model is 12.63, which indicates that the selection of the model significantly affects the result, and only 0.1% of the probability is due to model distortion caused by noise.

|   | KNO₃ (%) | NaNO₂ (%) | NaNO₃ (%) |
|---|----------|-----------|-----------|
| 1 | 0.45     | 0.45      | 0.1       |
| 2 | 0.1      | 0.1       | 0.8       |
| 3 | 0.333    | 0.333     | 0.333     |
| 4 | 0.2167   | 0.567     | 0.2167    |
| 5 | 0.8      | 0.1       | 0.1       |
| 6 | 0.1      | 0.45      | 0.45      |
| 7 | 0.5667   | 0.217     | 0.2167    |
| 8 | 0.2167   | 0.217     | 0.5667    |
| 9 | 0.1      | 0.8       | 0.1       |
|10 | 0.45     | 0.1       | 0.45      |
Table 4. Result of mixing experiment.

| Numbers | KNO₃ (%) | NaNO₂ (%) | NaNO₃ (%) | Before cleaning (g) | Cleaning after 2 min (g) | After complete cleaning (g) | Washed mass (g) | Total pollutant mass (g) | Decontamination percentage (%) |
|---------|----------|-----------|-----------|---------------------|--------------------------|----------------------------|----------------|--------------------------|-------------------------------|
| 2       | 0.45     | 0.45      | 0.1       | 69.9674             | 69.5898                  | 69.4936                    | 0.3776         | 0.4738                   | 79.70                         |
| 3       | 0.1      | 0.1       | 0.8       | 71.6597             | 71.312                   | 70.8017                    | 0.3477         | 0.858                    | 44.69                         |
| 4       | 0.3333   | 0.333     | 0.3333    | 69.6126             | 69.0731                  | 68.9974                    | 0.5395         | 0.6152                   | 87.70                         |
| 5       | 0.2167   | 0.567     | 0.2167    | 69.9673             | 69.4313                  | 69.3475                    | 0.536          | 0.6198                   | 86.48                         |
| 6       | 0.8      | 0.1       | 0.1       | 73.3021             | 72.8973                  | 72.8152                    | 0.4048         | 0.4869                   | 83.14                         |
| 7       | 0.1      | 0.45      | 0.45      | 73.7448             | 73.1612                  | 73.0752                    | 0.5836         | 0.6696                   | 87.16                         |
| 8       | 0.5667   | 0.217     | 0.2167    | 77.5899             | 77.1973                  | 76.9918                    | 0.3926         | 0.5981                   | 65.64                         |
| 9       | 0.2167   | 0.217     | 0.5667    | 73.4692             | 73.1493                  | 72.9859                    | 0.3199         | 0.4833                   | 66.19                         |
| 10      | 0.45     | 0.1       | 0.45      | 71.488              | 70.9327                  | 70.8426                    | 0.5553         | 0.6454                   | 86.04                         |
The error analysis of the response surface model shows that a certain difference is found between the predicted fitting degree and the adjusted fitting degree. Although it can be used, it is not an ideal value. In general, the signal-to-noise ratio (SNR) should be greater than four. In this response surface fitting, the SNR is 10.025, indicating that an appropriate signal is obtained, as shown in Table 7. The response surface significance analysis value indicates that this model can be used to guide this experiment.

According to the analysis, the optimized equation can be obtained as follows:

$$R = 8.85764 \times x_1 + 7.62517 \times x_2 + 4.2317 \times x_3 + 7.4179 \times x_1 \times x_3 + 13.13186 \times x_2 \times x_3,$$
where \( R \) represents the decontamination percentage for 2 min at 300°C;
X1 represents the percentage of KNO₃ in the mixture;
X2 represents the percentage of NaNO₂ in the mixture;
X3 represents the percentage of NaNO₃ in the mixture.

Response surface modeling. In accordance with the Design Expert software, the Quadratic model was selected for correction and analysis of the regression coefficient.

A response surface model was established for the contents of KNO₃, NaNO₂, and NaNO₃ that could affect the decontamination effect of multiple molten salts, as shown in Figure 6:

Figure 7 shows that line A represents potassium nitrate. When the percentage of potassium nitrate increases from 0.1 to 0.8, the clearance rate is unchanged. Line B, which represents sodium nitrite, initially increases and then decreases when the content percentage increases from 0.1 to 0.8. A significant fluctuation was found in the C line, representing the sodium nitrate content, and the clearance rate decreased rapidly after the sodium nitrate content was greater than 0.333.

The increase in NaNO₂ was beneficial to the progress of the reaction. If the concentration of Na⁺ is extremely high, the surface tension of the whole molten salt system is reduced. Thus, the influence of sodium nitrite on the cleaning effect initially increases and then decreases.

Optimal solution

The optimal solution is obtained according to the software.

As shown in Figure 8, the solution at this point is that the contents of KNO₃, NaNO₂, and NaNO₃ were 10%, 55%, and 35% respectively. The clearance rate should be 99.5% at this point. Several experiments were carried out in accordance with the optimal solution obtained from the equation. The experimental values
were maintained above 95%, thereby confirming that the fitted equation had a very high guiding reliability for the clearance rate.

**Comparison experiment of cleaning effect**

To verify the comparison between the new molten salt cleaning and the formula of the previous studies and other cleaning methods, the cleaning formula selected included the following: (1) KNO₃:NaNO₂ = 1:4, NaOH accounts for 30% of the total mass; (2) KNO₃:NaNO₂:NaNO₃ = 2:11:7, NaOH accounts for 30% of the
total mass; (3) kerosene; (4) special oil cleaning agent (heavy oil cleaning agent by 
2
900).

The valves, tellers, and cylinder bolts disassembled from the same engine were
selected for the comparative test. As shown in Figure 9, three types of components
should be cleaned, and four samples of each type correspond to 1, 2, 3, and 4 of the
cleaning methods.

We heated formula 1 and 2 of molten salt to 290°C, and placed the valve, tappet,
and bolt. On the basis of the previous research and experiments, the valve, bolt,
and the lifter were cleaned for 3, 4, and 3 min, respectively. We placed the valves,
lifters, and bolts into the container containing 3 and 4 solutions for 1 h. Then, they
were removed and scrubbed with steel wire balls for 15 min, and the surface cleaner
was removed.

Four groups of valves, tappets, and bolts with different cleaning methods were
compared with those before cleaning.

As shown in Figure 10, the surface cleaned with formula (1) molten salt reveals
a distinct metallic sheen. However, few stains are still found on the surface. The

Figure 9. Comparison of the experimental samples.
valve surface cleaned with molten salt of multiple nitric acid (2) has almost no carbon residue. The removal amount of carbon deposition is very small using kerosene (3) to clean the valve rod, but the place, where the carbon deposit is relatively thin is clean. The cleaning effect of the organic cleaning agent (4), cleaning valve, is worse than kerosene with less carbon removal.

Carbon deposition is a relatively thick and viscous pollutant. The principle of kerosene cleaning is that organic matter can only be dissolved by infiltration to remove carbon accumulation. After soaking, scrubbing can only remove the carbon deposited on the surface that has been soaked, but it cannot remove the carbon deposited near the substrate. The wetting ability of water-based cleaning agent is poor and the reaction is slow. Thus, it is the worst among the four methods.

As the main fastener in an engine, bolts are used to connect two parts. In the manufacturing process of high-strength bolts, cold heading, heat treatment, shot blasting, oblique correction, silk rubbing, phosphating treatment, and inspection are required.

High-strength bolts in the internal combustion engine industry are allowed for multiple use as long as they do not exceed the fatigue and shear limits. The comparison of four different cleaning methods of engine bolts indicates that bolts can be used many times if the torque is carried out in accordance with the regulations during assembly. If plastic deformation occurs, then it should be eliminated, as shown in Figure 11. Thus, the parts should be cleaned before deciding if they can be used again.

Bolt contaminant is mainly anti-loose glue; it is easy to decompose at high temperature, and the thickness is relatively thin. High-strength bolts should not be acid-washed but treated with hydrogen displacement because of the risk of hydrogen embrittlement. At present, the main methods used in the factory include high-pressure saturated steam cleaning, ultrasonic cleaning, grinding cleaning, and manual kerosene cleaning. These methods are inefficient, noisy, and not environmentally friendly.

Figure 10. Comparison of four different valve cleaning methods.

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The multicomponent molten salt cleaning can quickly remove the antirust paint on the bolt head and the antiloose glue in the thread. The comparison of the four methods of bolt cleaning clearly shows that the oil and the relaxation glue in the thread of the bolt surface area have been completely removed using methods (1) and (2). In methods (3) and (4), the oil is no longer evident, but a residual antiloose glue is still evident in the thread.

As shown in Figure 12, the four methods have good results in the cleaning of stiffeners. However, the surface of the tappet becomes yellow during cleaning, and controlling the cleaning time can prevent the surface from being oxidized.

The experiments show that the improved molten salt formula has a good decontamination capability at 290°C. Compared with the original formula of the optimal process, when the operating temperature is lower than the decomposition temperature of sodium nitrite, the decomposition of sodium nitrite, the production of nitrogen oxides, and the content of toxic gas contained in the exhaust gas are reduced, thereby showing a certain protective effect on the operator.

**Conclusion**

(1) Carbon deposition is not a process of continuous accumulation on the solid surface, but a process similar to a gelatinous bond composed of carbon deposition particles, metal particles, and completely burning
lubricating oil and fuel. It is an unbalanced thermodynamic and kinetic process driven by various physical and chemical actions.

(2) According to the optimal working temperature previously determined by the molten salt formula, the DSC, and image of the formula, sodium nitrite decomposes at work and produces nitrogen oxides, which are harmful to the human body. Thus, the working temperature should be reduced.

(3) The multicomponent mixed molten salt formula in the solar energy heat storage method indicates that the molten salt formula can be changed to maintain an excellent removal rate at low temperatures. With the mixed material experiment design, the contents of potassium nitrate, sodium nitrite, and sodium nitrate are 10%, 55%, and 35%, respectively. At this time, the effect of mixed salt cleaning is the best.

(4) The comparison between the previous optimal formulas with the improved mixed molten salt at 290°C confirmed that the cleaning effect of the new formula under the decomposition point of NaNO₂ is superior to that of binary molten salt. Compared with kerosene cleaning and water-based oil cleaning, the new molten salt formula has many advantages, such as high efficiency and thorough cleaning.

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