Cobalt-based alloy surfacing process optimization and surfacing material performance analysis

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Abstract
In order to solve the problem of the failure of the UMCo50 process burner, the orthogonal test was used to optimize the UMCo50 cobalt-based alloy TIG surfacing process, better joint performance was obtained for welding current of 120 A, surfacing speed of 12 cm min$^{-1}$, interpass temperature of 50 °C and surfacing layer of 2 ~ 3 layers; Tungsten inert gas (TIG) welding and plasma transferred arc weld (PTAW) surfacing were used to surfacing UMCo50 welding wire and T800 cobalt-based alloy powder on UMCo50 base metal. The structure, hardness, high temperature wear resistance and heat corrosion resistance of the surfacing layer were compared. The results show that UMCo50 surfacing layers are $\alpha$-Co (fcc) and $\varepsilon$-Co (hcp); T800 alloy surfacing layers are mainly Co$_3$Mo$_2$Si, CoMoSi, $\alpha$-Co and $\varepsilon$-Co. The Laves phase in the T800 alloy surfacing layer significantly improves its hardness and high temperature wear resistance; Under the same test conditions, the heat and corrosion resistance of the UMCo50 surfacing layer is significantly better than that of the T800 surfacing layer.

1. Introduction
With the rapid economic development, society’s demand for energy is gradually increasing, and oil resources are gradually depleted, which determines that coal will remain the dominant energy source for a long time. The direct combustion of coal produces soot, sulfur oxides, nitrogen oxides and a large amount of carbon dioxide, causing serious pollution to the environment. In addition, the direct combustion of coal cannot make full use of coal resources, the smoke will take away a lot of heat, and the slag still contains insufficiently burned charcoal. Therefore, vigorously developing clean coal technology and increasing coal utilization are important ways to solve the problem of the coordinated development of energy and the environment and meet society’s energy needs [1–3].

Coal water slurry (CWS) pressurized gasification technology is an important part of clean coal technology. CWS is a coal-based liquid fuel that emerged in the 1970s. It is a mixture of coal, water and chemical additives according to certain requirements. Furnace fuel or syngas raw material, with the advantages of stable combustion and low pollutant emissions [4–6]. The core equipment used in this field—special burners are usually also called process burners. They are mainly used to fully mix and atomize coal-water slurry and oxygen, and then spray into the high-temperature gasification furnace for rapid gasification reaction to obtain product synthesis in the process of CWS gasification, the process burner is affected by the erosion and corrosion of materials in the furnace and the high temperature heat flow. After a period of service, radial cracks will appear at the outlet of the outer nozzle, which makes the process burner gasification effect. Deterioration, reducing the working stability and service life of the process burner.

The process burner is usually forged from the cobalt-based alloy UMCo50, which is very expensive, each priced from hundreds of thousands to millions of yuan, and the service life is generally only about 40 days. In order to solve this problem, it is necessary to repair the process burner with UMCo50 as the surfacing material. UMCo50 cobalt-based alloy has excellent oxidation resistance, thermal shock resistance and corrosion resistance, especially in sulfur-containing oxidation environment, has very good thermal corrosion resistance to combustion products such as heavy oil or CWS [7].

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2. Material and methods

The base material of the surfacing test is forged UMCo50 cobalt-based alloy sheet, the sheet size is 10 mm × 10 mm × 6 mm, the chemical composition is shown in table 1, and the surfacing material is UMCo50 welding wire and T800 powder. The chemical composition is shown in tables 2 and 3. The analytical method for determining the chemical composition of substances is inductively coupled plasma optical emission spectrometer (ICP-OES).

In the surfacing process, there are many factors that affect the quality of the cobalt-based alloy surfacing layer, such as welding material specifications, the number of surface layers, surfacing speed, surfacing current, voltage, shielding gas flow, welding gun swing type, amplitude, preset thermal temperature, post-weld heat treatment, etc. If all process parameters are taken as influencing factors for orthogonal experimental design, the

| Factor         | Welding current (A) | surfacing speed (cm min⁻¹) | Interpass temperature (°C) | Number of surfacing layers |
|----------------|---------------------|----------------------------|---------------------------|---------------------------|
| level 1        | 100                 | 9                          | 50                        | 2                         |
| level 2        | 120                 | 10                         | 100                       | 3                         |
| level 3        | 140                 | 11                         | 150                       | 4                         |
| level 4        | 160                 | 12                         | 200                       | 5                         |
test workload is relatively large and the test cost is relatively high. Based on the requirements of improving the quality of the surfacing layer and reducing the cost of the test, select the factors that have a greater impact on the quality of the surfacing welding-surfacing current, surfacing welding speed, interpass temperature, and the number of surfacing layers for orthogonal test design. Choose 4 levels, the specific parameters are shown in table 4. According to the factor level table, the L16 (4^4) orthogonal test table can be selected. A total of 16 sets of tests are required. The corresponding process parameters of each set of tests are shown in table 5. According to the specified welding process parameters, the surfacing test is carried out, and the best process parameters are 120 A welding current, 12 cm min\(^{-1}\) surfacing speed, interpass temperature 50 °C, and 3 surfacing welding. According to the best process parameters, the surfacing welding was carried out on the circular test board and an x-ray inspection was carried out. The results showed that there were no defects such as porosity, inclusions, cracks, and so on in the surfacing layer. The welding process parameters could meet surfacing requirements. Figure 1 shows the macro-photograph and x-ray inspection diagram of the surfacing test board with the best process parameters.

Use plasma arc surfacing equipment to surface T800 cobalt-based alloy powder on a 10 mm × 10 mm × 6 mm test plate, preheating temperature 450 °C, transfer arc current 150 A, powder feeding rate 30 g min\(^{-1}\), swing speed 100 mm min\(^{-1}\), lateral speed 30 mm min\(^{-1}\), ion \(^{-1}\) gas flow rate 4 l min\(^{-1}\). Cut a 10 mm × 10 mm × 10 mm block sample from the surfacing layer, and then use SiC paper (\#2000) to polish the cross-section of the sample. After polishing, use W2.5 diamond polishing paste is polished on a polishing machine until the surface is bright and there are no scratches. Finally, an etchant (5gCuCl\(_2\) + 5gFeCl\(_2\) + 20 ml HNO\(_3\) + 80 ml HCl) is used to corrode the polished metal surface. The corrosion time is about 15 s. After corrosion, rinse off the residual corrosive agent on the surface immediately with clean water to prevent the corrosion from being too deep. After drying the sample, use the DM27700 universal metallographic analyzer to observe the microstructure of the corroded metallographic sample. A Druker D8 Discover x-ray diffractometer was used to perform x-ray diffraction on the sample to analyze the phase composition of the surfacing layer. The diffractometer uses a copper target as the emission source, the test voltage is 30 kV, the current is 50 mA, the scanning range is 20 ~ 100°, and the scanning speed is 8° min\(^{-1}\); JEOL JSM-6510 scanning electron microscope (SEM) is used to observe the microstructure; use the Shimadzu HMV-2T microhardness tester to measure the surface and cross-section of the surfacing layer. The loading force is 4.9 N (HV0.5), and the loading time is 15 s. When measuring the cross-sectional hardness, the measurement direction is perpendicular to the fusion line, and a point is taken every 0.25 mm from the surfacing layer to the substrate to measure and record; the MG-2000 high-temperature friction and wear tester is used to perform the friction and wear test on the surfacing layer. The loading force is 100 N, the test temperature is 650 °C, the speed is 240rp, the sliding distance of wear is 1800 m, the type of wear test is pin on disk, the material of the disc is GCr15, and the test time is 30 min. The hot corrosion test is carried out on the surfacing layer, and the corrosion medium is 75% Na\(_2\)SO\(_4\) + 25% NaCl (mass ratio) saturated salt solution.

### Table 5. Orthogonal test table.

| Test number | Welding current (A) | Surfacing speed (cm min\(^{-1}\)) | Interpass temperature (°C) | Number of surfacing layers |
|-------------|---------------------|-----------------------------------|-----------------------------|---------------------------|
| 1           | 100                 | 9                                 | 50                          | 2                         |
| 2           | 100                 | 10                                | 100                         | 3                         |
| 3           | 100                 | 11                                | 150                         | 4                         |
| 4           | 100                 | 12                                | 200                         | 5                         |
| 5           | 120                 | 9                                 | 100                         | 4                         |
| 6           | 120                 | 10                                | 50                          | 5                         |
| 7           | 120                 | 11                                | 200                         | 2                         |
| 8           | 120                 | 12                                | 150                         | 3                         |
| 9           | 140                 | 9                                 | 150                         | 5                         |
| 10          | 140                 | 10                                | 200                         | 4                         |
| 11          | 140                 | 11                                | 50                          | 3                         |
| 12          | 140                 | 12                                | 100                         | 2                         |
| 13          | 160                 | 9                                 | 200                         | 3                         |
| 14          | 160                 | 10                                | 150                         | 2                         |
| 15          | 160                 | 11                                | 100                         | 5                         |
| 16          | 160                 | 12                                | 50                          | 4                         |
3. Results and discussion

3.1. Microstructure of surfacing layer

The fusion zone is the boundary area between the weld and the base metal, also called the semi-melted zone. The most important feature of the fusion zone is that it has obvious chemical inhomogeneities, and at the same time there are physical inhomogeneities. The structure of this area is very coarse, the superheated structure is obtained after cooling, and the plasticity and toughness are extremely poor. It is the weakest link of the welded joint, and it often becomes the origin of cracks and brittle failure \[8\].

The microstructure of the surfacing layer is shown in figure 2. The UMCo50 surfacing layer is well combined with the base metal, and no defects such as cracks and holes are found; the thick columnar crystals grow perpendicular to the fusion line to the center of the surfacing layer, with obvious directionality. The grains are

![Figure 2. Metallographic structure: (a) near the fusion line of UMCo50; (b) center of UMCo50 surfacing layer; (C) Near the T800 fusion line; (d) The center of the T800 surfacing layer.](image1)

![Figure 3. X-ray diffraction pattern of UMCo50 surfacing layer (a); x-ray diffraction pattern of T800 surfacing layer (b).](image2)
approximately parallel. During the surfacing process, the molten pool is small in volume and overheated, and it is surrounded by a lower temperature base material. Therefore, the temperature gradient near the fusion line is large. The molten metal mainly dissipates heat through the base material, and the crystals dissipate heat along the way. It grows into columnar crystals in the opposite direction; no defects such as cracks and pores are found near the fusion line of the T800 alloy surfacing layer, and the surfacing layer is metallurgically bonded with the base metal. The surfacing layer structure is mainly composed of white block structure and gray structure. From the fusion line to the center of the surfacing layer, the gray structure gradually increases.

3.2. Surfacing layer structure

In order to analyze the influence of ultrasonic vibration on the phases of the surfacing layer, x-ray diffraction analysis was performed on the surfacing layer. The test results are shown in figure 5. The phases of the UMCo50 surfacing layer are both $\alpha$-Co (fcc) and $\varepsilon$-Co (Hcp). Cobalt has a stable hexagonal close-packed structure (hcp) at room temperature and transforms into a face-centered cubic structure (fcc) above 417 °C. When cooling from high temperature, $\alpha$-Co $\rightarrow$ $\varepsilon$-Co transformation will occur, which is a non-diffusion phase transformation, also known as martensitic transformation. However, this transformation is extremely slow, so cobalt still exists in a

![Figure 4. Micro morphology of UMCo50 surfacing layer (a); Micro morphology of T800 surfacing layer (b).](image)

![Figure 5. Microhardness distribution of T800 and UMCo50 surfacing layers.](image)

| Region | Co  | Cr  | Fe  | Si  | Mo  | Ni  |
|-------|-----|-----|-----|-----|-----|-----|
| A     | 35.22 | 16.34 | 6.53 | 3.75 | 32.36 | 5.80 |
| B     | 38.44 | 23.63 | 8.76 | 2.58 | 12.32 | 3.95 |
| C     | 48.76 | 17.43 | 7.23 | 3.86 | 28.33 | 4.71 |

![Table 6. EDS analysis of T800 surfacing layer (wt.%).](image)
face-centered cubic structure at room temperature. The addition of Cr in the cobalt-based alloy can increase the martensite transformation temperature and stabilize the existence of \(\varepsilon\)-Co \([9–11]\).

Therefore, there are both \(\alpha\)-Co (fcc) and \(\varepsilon\)-Co (hcp) in the UMCo50 surfacing layer \([12]\); the phases of the T800 alloy surfacing layer are mainly Co₃Mo₂Si, CoMoSi, \(\alpha\)-Co and \(\varepsilon\)-Co, among which Co₃Mo₂Si and CoMoSi are a kind of Laves phase, has a relatively complex atomic structure, and has high hardness and strength even at high temperatures \([13–15]\).

Figure 4 shows the scanning morphology of UMCo50 surfacing layer under different ultrasonic amplitudes. On the surfacing layer matrix, there is an interlaced network of flake structure, and no precipitates are seen in the surfacing layer; the structure of the T800 surfacing layer is small and white and it is composed of structure, gray bump phase and gray large block structure. The energy spectrum analysis of A, B, and C regions are performed. The results are shown in table 6. The C region contains more Co elements, while Mo and Si elements are less. According to the element content of A, B, and C and XRD results, it can be judged that the A and B regions are Laves phases rich in Si and Mo elements, and the C region is a cobalt-based solid solution.

### 3.3. Hardness

Figure 5 shows the microhardness distribution of T800 and UMCo50 surfacing layers. It can be seen that the microhardness distributions of the two alloy surfacing layers are significantly different in different areas. The average microhardness of the base metal of UMCo50 is about 340 HV. In the layer, the hardness near the fusion line is slightly lower than that of the base metal. As the distance from the fusion line increases, the microhardness of the surfacing layer gradually decreases and tends to stabilize. The average microhardness of the UMCo50 surfacing layer is about 270 HV. In the T800 surfacing layer, the hardness near the fusion line is significantly higher than that of the base metal. As the distance from the fusion line increases, the microhardness rises rapidly and eventually stabilizes. The average microhardness of the surfacing layer is about 660 HV. It is about 2.4 times the hardness of UMCo50 surfacing layer.

The Archard equation is widely used in a large number of documents. It describes the relationship between material wear, applied load, sliding distance and material hardness during wear \([16]\):

\[
V = kF\frac{S}{H}
\]

Where \(V\) is the volume of material removed, \(k\) is the wear coefficient, \(F\) is the applied normal load, \(S\) is the sliding distance, and \(H\) is the hardness of the material. The wear coefficient \(k\) is a coefficient obtained through experiments in the law of wear, which is specific to the parameters and environment of each test. Through Archard’s wear equation, it can be seen that the hardness of the material is inversely proportional to the amount of wear. The previous hardness test shows that the hardness of T800 is greater than UMCo50, which can explain why the wear of T800 is less than UMCo50. Finally, it is concluded that higher hardness has conducive to improving wear resistance.

### 3.4. High temperature wear test

The high temperature wear test of the T800 alloy surfacing layer is carried out. The wear rates of the surfacing layer sample is shown in figure 6. The wear rate of the T800 surfacing layer is \(6.67 \times 10^{-3}\) mg m \(^{-1}\), and the wear rate of the UMCo50 surfacing layer is \(2.056 \times 10^{-2}\) mg m \(^{-1}\). It shows that under the same test conditions, the high temperature wear resistance of the T800 surfacing layer is much higher than that of the UMCo50 surfacing layer. The high hardness and excellent high temperature wear resistance of the T800 surfacing layer depend on
the Laves phases such as Co₃Mo₂Si and CoMoSi generated in the surfacing layer. The combination of the Laves phase with higher hardness and the cobalt-based solid solution with better toughness can improve the hardness and strength of the surfacing layer. When worn, the cobalt-based solid solution with better toughness is the first to be worn to the abrasive material, making the Laves phase with higher hardness gradually stand out. The existence of the Laves phase can resist the continued wear of the material and improve the wear resistance of the material, when it reaches a certain level, the Laves phase is broken and peeled off under the action of external force [17–19].

Figure 7 shows the representative coefficients of friction (COF) recorded in the high temperature wear test for UMCo50 and T800. At the beginning of the test, the COF of UMCo50 continued to increase, reaching a peak in about 4 min, and then entering the running-in period, the running-in time was about 8 min, and then reached a relatively stable value of 0.8. One minute after the start of the test, the COF of T800 reached its peak, and then entered a 5 min running-in period, and finally reached a relatively stable value of 0.67. Compared with UMCo50, T800 has a shorter run-in period, and the stable COF is also less than UMCo50. Although it hardly directly relates the COF to the wear loss of the material, the friction may be affected by many factors in the wear process, such as the defect of the test material, the vibration of the test machine, the roughness of the wear surface, etc. Therefore, the low coefficients of friction may correspond to lower wear loss [20–22].

It can be seen from figure 8 that the wear surface of the sample has narrow and deep furrows along the friction direction, and obvious adhesion marks are found on the surface. Therefore, the wear mechanism of the surfacing layer is mainly abrasive wear and adhesive wear. The structure of UMCo50 surfacing layer is α-Co (fcc) and ε-Co (hcp). Compared with the GCr15 after quenching, the hardness is lower and the toughness is better. When the tangential force of the abrasive grains occurs along the friction surface during movement, the UMCo50 surfacing layer with lower hardness will be sheared, ploughed or cut by abrasive grains, and plastically deformed, forming furrows on the surface of the base metal. Most of the ploughed surface material follows the
direction of the hard particles and it accumulates on both sides of the furrow and peels off under the continuous action of abrasive grains, resulting in weight loss of the surfacing layer. There are shallow furrows on the surface of the T800 surfacing layer, no obvious scratches are found, there are small particles peeling off on the worn surface, and cracks are generated. This is due to the relative sliding between the grinding disc and the surface of the sample, and the surfacing layer is squeezed, so that part of the surfacing layer material and oxide film will peel off to form debris, resulting in cracks. These small peeled debris will act as abrasive particles to the surface of the weld layer is extruded and cut, so the wear mechanism of the T800 surfacing layer is abrasive wear.

The energy spectrum analysis of the wear surface of the UMCo50 surfacing layer is shown in table 7. It can be seen that the wear surface contains more O and Fe elements, indicating that an oxide film is formed on the wear surface during high temperature wear. The existence of the oxide film can lubricate wear surface, it has a certain

### Table 7. UMCo50 surfacing layer wear surface element content (wt.%).

|     | Co  | Cr  | Fe  | O   |
|-----|-----|-----|-----|-----|
|     | 38.70 | 19.74 | 21.04 | 20.51 |

### Table 8. T800 surfacing layer wear surface element content (wt.%).

|     | Co  | Cr  | Fe  | Ni  | Si  | Mo  | O   |
|-----|-----|-----|-----|-----|-----|-----|-----|
|     | 31.25 | 16.12 | 12.04 | 1.77 | 2.13 | 16.42 | 20.26 |

![Figure 9. Corrosion kinetic curve of surfacing layer at 1000 °C.](image)

![Figure 10. XRD pattern of UMCo50 surfacing layer surface after hot corrosion (a) XRD pattern of T800 surfacing layer surface after hot corrosion (b).](image)
inhibitory effect on wear, but the strength of the oxide film is relatively low. When the abrasive material is cut and squeezed, the oxide film is prone to peeling off, exposing the material to a new surface, which is then oxidized, and then the oxide film peels off again, and the material is gradually lost. Therefore, there is oxidative wear in the wear process, but the wear rate is very small, and the contribution to weight loss is small. The energy spectrum analysis of the worn surface of the T800 surfacing layer is shown in table 8. It can be seen that the worn surface contains more O and Fe elements. Due to the poor toughness of the T800 surfacing layer, the oxide film is more likely to crack and peel off, so oxidative wear is also a cause of material loss [23, 24].

3.5. High temperature corrosion

Figure 9 is the corrosion kinetics curve of UMCo50 and T800 surfacing layer in 75% Na2SO4 + 25% NaCl (mass ratio) corrosion medium at 1000 °C. It can be seen that with the increase of time, the weight loss of the UMCo50 and T800 surfacing layer continues to increase. In each time period, the corrosion weight loss of the T800 surfacing layer is significantly higher than that of the UMCo50 surfacing layer. It can be seen that the heat corrosion resistance of UMCo50 is higher than that of the T800 alloy surfacing layer.

The x-ray diffraction analysis results of UMCo50 surfacing layer and T800 surfacing layer after thermal corrosion at 1000 °C for 72 h are shown in figure 10. The results show that the corrosion products of UMCo50 surfacing layer are mainly CoO, Cr2O3, CoCr2O4, Fe3O4, Fe2O3; The corrosion products of T800 surfacing layer after thermal corrosion are mainly composed of Cr2O3, CoCr2O4, Fe3O4, Fe2O3, NiO and SiO2. Cr2O3 and CoCr2O4 have a protective effect on the base metal. The corrosion mechanism of T800 surfacing layer is basically the same as that of UMCo50 surfacing layer, mainly including the formation and destruction of Cr2O3 oxide film. The difference in heat corrosion resistance of UMCo50 and T800 surfacing layers is mainly related to the content of Cr. The content of Cr in UMCo50 alloy is higher than that of T800 alloy, so it can form a denser and continuous oxide film, which can better protect the base metal from being damaged corrosion. In addition, T800 alloy contains more Mo elements. Mo oxides will lower the melting point of Na2SO4 salt precipitation. More Mo elements will reduce the thermal corrosion resistance of the T800 surfacing layer.

Hot corrosion includes the interaction between the deposited salt film and the oxide film, as well as the sulfidation-oxidation of the alloy and the corrosive medium. The melting point of Na2SO4 is 884 °C and that of NaCl is 801 °C. At 1000 °C, the mixed salt of 75% Na2SO4 + 25% NaCl (mass ratio) adheres to the metal surface in a liquid state. At the beginning of hot corrosion, oxygen in the air first oxidizes selectively with alloying elements. The affinity of Cr and oxygen is stronger than that of other alloying elements, so a dense Cr2O3 film and spinel composite oxide CoCr2O4 (CoO-Cr2O3) are formed on the surface of the material, they have a protective effect on the base metal and can prevent the further diffusion of sulfur and oxygen into the alloy [25]. With the continuous growth of the oxide film, the oxide film interacts with Na2SO4 to cause alkaline melting [26, 27]. The reaction formula is as follows:

\[
\text{Cr}_2\text{O}_3 + 2\text{O}^{2-} + \frac{3}{2}\text{O}_2 \rightarrow 2\text{Cr}_2\text{O}_4^{2-}
\]

The dissolved Cr2O42− diffuses to the interface between Na2SO4 and air, and the following reactions occur, forming loose and porous oxides, losing the protective effect on the base metal:

\[
2\text{Cr}_2\text{O}_4^{2-} \rightarrow \text{Cr}_2\text{O}_3 + 2\text{O}^{2-} + \frac{3}{2}\text{O}_2
\]

With the dissolution of the oxide film, S element diffuses inward along the grain boundary and interacts with the metal element M in the matrix to form sulfide MS. MS is oxidized and reduced S, and the reduced S reacts with M to form MS. This cycle accelerates the corrosion of the alloy.

4. Conclusions

(1) The phases of the UMCo50 surfacing layer are α-Co (fcc) and ε-Co (hcp); the phases of the T800 alloy surfacing layer are mainly Co3Mo2Si, CoMoSi, α-Co and ε-Co.

(2) The hardness of the T800 alloy surfacing layer is higher than that of the UMCo50 surfacing layer; the wear resistance of the T800 alloy surfacing layer at 650 °C is better than that of the UMCo50 surfacing layer. The uniformly distributed carbide and Laves phase are the main reasons.

(3) Under the test conditions of 1000 °C, 75% Na2SO4 + 25% NaCl (mass ratio) corrosive medium, UMCo50 and T800 surfacing layers have formed protective Cr2O3 and CoCr2O4 oxide films, but because the UMCo50 surfacing layer contains more Cr element, so the corrosion resistance is better than T800 surfacing layer.
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