Temperature and Stress Simulation of the Hardfacing for Cr5Mo1V-RE Alloy

Various technological parameters and experimental verification were used to compare the weldability of two alloys

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ABSTRACT

The temperature field and stress field for hardfacing Cr5Mo1V and Cr5Mo1V-RE alloys were simulated to compare their weldability. Subsequently, those for hardfacing Cr5Mo1V-RE alloy using various technological parameters were researched systematically. The results indicate that the computational temperature field and stress field agree well with the experimental results, and the errors are smaller than 5%. For Cr5Mo1V-RE alloy, the peak stresses are smaller than those for Cr5Mo1V alloy, which indicates the weldability of Cr5Mo1V-RE alloy is more excellent than that of Cr5Mo1V. The decreasing of $\sigma_x$ and $\sigma_y$ can both contribute to decreasing of the stress for Cr5Mo1V-RE alloy, in which the decline of the longitudinal stress $\sigma_y$ plays the major role. The hardfacing velocity influences the peak stress at the hardfacing initial state and the stress-influenced areas at cold state. The greater the hardfacing velocity, the lesser is the peak stress at the hardfacing initial state and smaller is the stress-influenced area at the cold state. The preheating temperature only influences the peak stress at the hardfacing initial state. When the preheating temperature increases to 150°C, the peak stress decreases drastically.

KEYWORDS
- Temperature and Stress Fields
- Simulation
- Experimental Verification
- Hardfacing
- Technological Parameters

Introduction

A Cr5Mo1V supporting roller is the key component in steel rolling production, which plays an important role in supporting the cool-rolling work roller (Refs. 1, 2). During its work process, the Cr5Mo1V supporting roller bears mechanical, fatigue, and friction loads. After being in service for a period of time, it may fail due to mechanical fatigue and excessive wear (Refs. 3, 4). The failed supporting roller can be repaired by the hardfacing method to restore its dimension and shape, and to obtain higher performance (Refs. 5–7).

In order to ensure the repaired supporting roller has excellent mechanical properties, the composition of the hardfacing alloy should be optimized. Our team’s previous research indicated that by adding an appropriate amount of rare earth (RE) elements in the Cr5Mo1V, the mechanical properties of the hardfacing alloy, such as hardness, strength, wear resistance, and toughness, are all increased (Refs. 8, 9).

However, for the hardfacing alloys, compared with the mechanical properties, the weldability is more important. Excellent weldability is considered to be the prerequisite for the application of the hardfacing alloys (Refs. 10–12). Therefore, before the high-performance hardfacing alloy (Cr5Mo1V-RE) is used to replace the traditional Cr5Mo1V alloy for repair of the failed supporting roller, their weldability should be compared. Moreover, the hardfacing process parameters for the Cr5Mo1V-RE alloy should be optimized.

Simulation of the hardfacing process using numerical methods can be employed to predict welding deformation, stress distribution, and other hardfacing attributes, and thus can partially replace the expensive, time-consuming experimental-based trial-and-error method of determining weldability and development of hardfacing process parameters (Ref. 13). Lazić (Ref. 14) researched the temperature field during the hardfacing process by numerical simulation, and indicated the calculated results are consistent with the experimental results. Joshi (Ref. 15) adjusted the welding heat source parameters in Goldak’s double-ellipsoidal model using SysWELD simulation, and showed that the optimized parameters are more suitable for hardfacing. The results showed excellent matching with the experimental ones. Li (Ref. 16) focused on the simulation of process stress of medium-high-carbon steel during martensite transformation after hardfacing, and indicated that the compressive stress appeared on the surface of the specimen during the hardfacing cooling process when martensite transformation occurs, while the large tensile stress appeared on the surface of the speci-
men and was held to room temperature with the increasing of the time. The results are beneficial to improving hardfacing alloy composition and optimizing the hardfacing technological parameters.

In this work, the temperature field and stress field for hardfacing Cr5Mo1V alloy were simulated and the results were compared with the experimental ones to verify the reliability of the simulation. Then those for hardfacing Cr5Mo1V-RE alloy using various technological parameters were researched systematically, which cannot only investigate the weldability of Cr5Mo1V-RE alloy but also provide the basis for optimizing hardfacing process parameters.

Materials and Methods

Experimental Procedure

A hardfacing experiment was carried out on Cr5Mo1V alloy thin sheet by Cr5Mo1V alloy flux-cored wire using a Lincoln 588 hardacing machine. The thin sheet was in the dimension of 100 × 40 × 10 mm with a 100 × 12 × 3-mm groove on its surface, which is shown in Fig. 1A. The hardfacing was made using the following parameters: 25 V welding voltage, 260 A welding current, 5 mm/s welding speed, and 10 L/min flow rate of argon shielding gas. The thermal cycles were recorded using K-type thermocouples spot welded at different locations. The stresses were measured using an ultrasonic technique described in detail by Palanichamy (Ref. 17).

Model Building

The finite element model for hardfacing simulation, which was 100 × 40 × 10 mm and consistent with the actual sample size, was established by modeling software Visual-mesh — Fig. 1B. In order to reduce the computational work, the hardfacing alloy was approximated to a rectangular shape with the dimensions of 100 × 12 × 3 mm, which was the actual size of the single-pass hardfacing alloy. Beside that, the meshes in the hardfacing alloy area were dense, while those in the matrix area were sparse — Fig. 2. After meshing, 56,041 units and 63,136 nodes were in the model. Subsequently, the welding groups were configured, in which the overall model was set to ALL, the matrix area was set to BASE, the hardfacing alloy area was set to ADD, and the outer surfaces was set to HEAT. Moreover, welding line WEL, reference line REFL, welding starting node SN, welding end node EN, and welding starting unit SE were set according to Fig. 3.

Heat Source Determination

Conical heat source (Ref. 18), Gaussian heat source (Ref. 19), and double-ellipsoid heat source (Refs. 20, 21) are the common heat sources for welding simulation, in which double-ellipsoid heat source is particularly applicable to the condition that the heat input distribution range is large (Refs. 15, 22). Therefore, in this work, the double-ellipsoid heat source was selected as the hardfacing heat source. The model uses the following equation to define the volumetric heat flux \( q \) inside the front and rear regions of the heat source, where these regions are denoted by the subscripts 1 and 2, respectively:

\[
q_{1,2}(x,y,z,t) = \frac{6\sqrt{\pi}f_{1,2}Q}{abc_1,2}\left(\frac{3a^2 - 3y^2 - 3z^2}{a^2} e^{-\frac{y^2}{a^2}} e^{-\frac{z^2}{b^2}} e^{-\frac{z^2}{c^2}}\right) \tag{1}
\]

in which, \( a, b, \) and \( c \) describe the dimensions of the heat source, \( Q \) is the power input from the welding source, \( v \) is the welding velocity, \( t \) is the time, \( \tau \) is a lag factor defining the position of the heat source at \( t = 0 \), and \( f \) defines the fraction of the heat deposited in either region. Figure 4 shows the configuration of the double-ellipsoid heat source.
Material Library Establishment

The parameters of the Cr5Mo1V and Cr5Mo1V-RE alloys were calculated by experiments, JMat Pro® software, and the differential analytical method. The specific heat, thermal conductivity, and density for simulating the thermal field are listed in Table 1, while the elasticity modulus, Poisson’s ratio, thermal strain, and yield strength for simulating the stress field are listed in Table 2. The CCT curves for the two alloys are shown in Fig. 5.

Initial and Boundary Conditions

Hardfacing simulation was conducted at room temperature. The initial temperature was noted as 25°C. Convective and radiation losses on the model surfaces were taken into account. Given a body temperature T, surrounded by a fluid or gas, radiation to the surrounding medium follows the Stefan-Boltzmann law and heat convection assumes that a thermal layer exists with a heat transfer coefficient, which follows Newton’s law of cooling. These boundary conditions were applied to the model by specifying the value of combined heat transfer coefficient and the surrounding temperatures to the surface by creating a skin for the model. Force-free

Table 1 — Parameters of Cr5Mo1V Alloy and Cr5Mo1V-RE Alloy for Simulating the Thermal Field

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>0</th>
<th>200</th>
<th>900</th>
<th>1100</th>
<th>1400</th>
<th>2500</th>
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<tr>
<td>Cr5Mo1V alloy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Heat (J/kgK)</td>
<td>510</td>
<td>530</td>
<td>700</td>
<td>590</td>
<td>630</td>
<td>707</td>
</tr>
<tr>
<td>Thermal Conductivity (W/mm)</td>
<td>0.034</td>
<td>0.034</td>
<td>0.026</td>
<td>0.021</td>
<td>0.033</td>
<td>0.033</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>7.61</td>
<td>7.48</td>
<td>7.35</td>
<td>7.26</td>
<td>7.03</td>
<td>6.85</td>
</tr>
<tr>
<td>Cr5Mo1V-RE alloy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Heat (J/kgK)</td>
<td>430</td>
<td>550</td>
<td>565</td>
<td>596</td>
<td>638</td>
<td>707</td>
</tr>
<tr>
<td>Thermal Conductivity (W/mm)</td>
<td>0.046</td>
<td>0.046</td>
<td>0.022</td>
<td>0.028</td>
<td>0.032</td>
<td>0.032</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>7.82</td>
<td>7.63</td>
<td>7.46</td>
<td>7.43</td>
<td>7.34</td>
<td>7.29</td>
</tr>
</tbody>
</table>
clamping was considered at the corners of the weld plate with elastic constraints of 1 N/mm. It means that the clamping is not rigid.

Results and Discussion

Thermal and Stress Fields for Cr5Mo1V Compared with Experimental Results

In order to verify the reliability of the calculation, the thermal field and stress field for hardfacing Cr5Mo1V alloy were researched and compared with the experimental results. During the process, the hardfacing heat source was the double-ellipsoid heat source, as determined in Fig. 4, the ambient temperature and the initial matrix temperature were 20°C, and the hardfacing velocity was 5 mm/s. Moreover, the hardfacing alloy (ADD area) and the matrix metal (BASE area) were both set to the Cr5Mo1V alloy.

Before the calculation, the heat source used under the current conditions must be determined. After a complex parameter correction, the accurate heat source parameters can be obtained. The hardfacing bead cross section obtained by finite element analysis was compared with that obtained by actual hardfacing, as shown in Fig. 6. It was found that there is good agreement between the simulated bead cross section and actual hardfacing one. It can be inferred that the heat source parameters are applicable, in which \( Q = 4800 \) W, \( q_1 = 128 \) W/mm², \( q_2 = 97 \) W/mm², \( c_1 = 1.6 \) mm, \( c_2 = 2.8 \) mm, \( a = 2.4 \) mm, \( b = 3.6 \) mm, and \( v = 5 \) mm/s.

The calculated thermal fields for Cr5Mo1V alloy hardfacing models at 1.2, 6, 15, 20, 49.5, and 1000 s are shown in Fig. 7. When the hardfacing time was 1.2 s, the temperature was low and the peak value was only 1570°C, as shown in Fig. 7A. With an increase in the hardfacing time (Fig. 7A–D), the peak temperature increased consistently at 1892°C, 1927°C, and 2185°C when the hardfacing times were 6, 15, and 20 s. Moreover, during hardfacing (0–20 s), the temperature gradient before the heat source was sharp while that behind the heat source was gentle. On cooling, as shown in Fig. 7D–F, the highest temperature area moved toward the center gradually. When the hardfacing systems were cooled completely (1000 s, shown in Fig. 7F), the temperature of each area was basically the same.

After the thermal fields at different times were observed, the temperature variation tendencies for different positions on the hardfacing model were investigated. First, five measuring points were selected isometrically along the centerline of the hardfacing alloy, which are points A, B, C, D, and E, and the nodes are 2992, 5260, 7528, 9607, and 11,497. Subsequently, by determining point A as the reference point, another five measuring points were selected isometrically perpendicular to the cen-

| Table 2 — Parameters of Cr5Mo1V Alloy and Cr5Mo1V-RE Alloy for Simulating the Stress Field |
|------------------------|-------|-------|-------|-------|-------|-------|
| Temperature (°C)       | 20    | 200   | 500   | 900   | 1250  | 1400  |
| Cr5Mo1V Alloy          |
| Elasticity Modulus (N/mm²) | 210000 | 200000 | 140000 | 94000 | 3350 | 1000 |
| Poisson’s Ratio        | 0.33  | 0.33  | 0.33  | 0.33  | 0.33 | 0.33 |
| Thermal Strain (%)     | 0     | 0.004 | 0.008 | 0.0128| 0.0192| 0.0208|
| Thermal Expansion Coefficient (1E-6/K) | 12.2  | 12.8  | 14.5  | 24.3  | 38.7 | 47.4 |
| Tensile Strength (N/mm²) | 510   | 467   | 237   | 84    | 10   | 10   |
| Yield Strength (N/mm²) | 390   | 258   | 187   | 45    | 5    | 5    |
| Cr5Mo1V-RE Alloy       |
| Elasticity Modulus (N/mm²) | 210000 | 210000 | 135000 | 3000 | 1000 | 1000 |
| Poisson’s Ratio        | 0.33  | 0.33  | 0.33  | 0.33  | 0.33 | 0.33 |
| Thermal Strain (%)     | 0     | 0.003 | 0.009 | 0.013 | 0.019| 0.021|
| Thermal Expansion Coefficient (1E-6/K) | 12.4  | 13.2  | 15.1  | 26.4  | 42.3 | 49.2 |
| Tensile Strength (N/mm²) | 485   | 384   | 213   | 46    | 10   | 10   |
| Yield Strength (N/mm²) | 340   | 231   | 150   | 13    | 5    | 5    |
terline of the hardfacing alloy, which are points A, F, G, H, and I, and the nodes are 2992, 3094, 73, 168, 3150, and 3128, respectively. The measuring points on the hardfacing model for simulation are given in Fig. 8.

Figure 9 indicates the temperatures on the measuring points along the hardfacing alloy centerline (A, B, C, D, and E) by calculation and experiment at different times. The computational results agree well with the experimental results, and the errors were smaller than 5%. The temperature variation tendencies of the points along the hardfacing alloy centerline were similar, in which the hardfacing heat source moved from far to near,

Fig. 7 — Thermal fields for Cr5Mo1V alloy hardfacing models at different times: A — 1.2 s; B — 6 s; C — 15 s; D — 20 s; E — 49.5 s; F — 1000 s.

Fig. 8 — Measuring points on the hardfacing model for simulation.
the temperature of the point rose sharply and reached the peak when the welding heat source arrived at the point. Subsequently, when the hardfacing heat source moved away, the temperature reduced gradually and the reduced speed was far lower than the rising speed. What is more, the temperature of each point ultimately tended to be uniform.

Figure 10 illustrates the temperatures on the measuring points that were perpendicular to the hardfacing alloy centerline (A, F, G, H, and I) at different times. When the hardfacing heat source passed by the point on the hardfacing alloy centerline (point A), the temperatures of all the points rose at first but then reduced, and the temperatures rose faster than they reduced. Moreover, the temperature change on point A was very sharp and the peak temperature was high, 1889°C. With increase of the distance to the hardfacing alloy centerline, the temperature changes were smooth and the peak temperatures were reduced gradually, 1260°C, 500°C, 318°C, and 296°C for points F, G, H, and I, respectively.

The calculated stress fields for Cr5Mo1V alloy hardfacing models at 1.2, 6.2, 14.8, 20, 49.5, and 1000 s are shown in Fig. 11. When the hardfacing time was 1.2 s because the matrix metal was near the hardfacing alloy (Fig. 11A), which can be considered the heat-affect ed zone (HAZ), was heated to high temperature rapidly with the volume expansion (as shown in Fig. 7A), the large stress appeared, and the value was 247.8 MPa. Meanwhile, the hardfacing alloy was under the condition of melting, so the stress on it was 0 MPa. With an increase in the hardfacing time, as shown in Fig. 11B–D, the large stresses were always focused on the HAZs, and the peak stresses rose gradually to 453.2, 615.8, and 631.2 MPa when the hardfacing times were 6.2, 14.8, and 20 s. At the same time, because the hardfacing alloys were cooled gradually, the stresses also appeared on them. In cooling, the stresses rose sequentially, and the peak stress reached 755.1 MPa when the hardfacing system was cooled completely, as shown in Fig. 11F.

Computational and experimental longitudinal stress \( \sigma \) distribution along the hardfacing alloy centerline after the hardfacing system was cooled completely is given in Fig. 12. The computational result agrees well with the experimental

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value Used</th>
</tr>
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<tbody>
<tr>
<td>( Q ) (W)</td>
<td>4800</td>
</tr>
<tr>
<td>( q_1 ) (W/mm³)</td>
<td>141</td>
</tr>
<tr>
<td>( q_2 ) (W/mm³)</td>
<td>104</td>
</tr>
<tr>
<td>( c_1 ) (mm)</td>
<td>1.7</td>
</tr>
<tr>
<td>( c_2 ) (mm)</td>
<td>3.5</td>
</tr>
<tr>
<td>( a ) (mm)</td>
<td>2.1</td>
</tr>
<tr>
<td>( b ) (mm)</td>
<td>3.1</td>
</tr>
<tr>
<td>( v ) (mm/s)</td>
<td>3</td>
</tr>
<tr>
<td>( v_0 ) (mm/s)</td>
<td>7</td>
</tr>
</tbody>
</table>
The longitudinal stress $\sigma_y$, which was caused by the longitudinal shrinkage of the hardfacing alloy, was coupled by tensile stress ($\sigma_y > 0$ MPa) and compressive stress ($\sigma_y < 0$ MPa). Moreover, in most areas, the $\sigma_y$ was mainly contributed by tensile stress, and tended to be stable in the central zone, which was near 0 MPa. While in the hardfacing ending zone, because of the applied constraint, the large compressive stress of 192 MPa existed.

Figure 13 indicates the computational and experimental transverse stress $\sigma_x$ distribution along the hardfacing alloy centerline after the hardfacing system was cooled completely. The transverse stress $\sigma_x$ is tensile stress ($\sigma_x > 0$ MPa) and the stress peak is 158 MPa. Moreover, $\sigma_x$ in the central zone is large while that in the fringe area is small, which is contrary to that of $\sigma_y$.

Figure 11 — Stress fields for the Cr5Mo1V alloy hardfacing models at different times: A — 1.2 s; B — 6.2 s; C — 14.8 s; D — 20 s; E — 49.5 s; F — 1000 s.

Thermal Field and Stress Field for Cr5Mo1V-RE Alloy

After verifying the accuracy for simulation, the simulation for Cr5Mo1V-RE alloy was conducted to compare the weldability between Cr5Mo1V alloy and Cr5Mo1V-RE alloy. The hardfacing alloy was set to Cr5Mo1V-RE, and the heat source parameters were adjusted by comparing the hardfacing bead cross section from simulation with that from actual hardfacing, in which $Q = 4800$ W, $q_1 = 112$ W/mm$^3$, $q_2 = 84$ W/mm$^3$, $c_1 = 1.8$ mm, $c_2 = 3.1$ mm, $a = 2.2$ mm, $b = 4.1$ mm, and $v = 5$ mm/s.

The thermal fields for Cr5Mo1V-RE
Fig. 12 — Computational and experimental longitudinal stress $\sigma_y$ distribution along the hardfacing alloy centerline for Cr5Mo1V alloy at cold state (1000 s).

Fig. 13 — Computational and experimental transverse stress $\sigma_x$ distribution along the hardfacing alloy centerline for Cr5Mo1V alloy at cold state (1000 s).

Fig. 14 — Thermal fields for Cr5Mo1V-RE alloy hardfacing models at different times: A — 1.2 s; B — 6 s; C — 15 s; D — 20 s; E — 49.5 s; F — 1000 s.
alloy hardfacing models at 1.2, 6, 15, 20, 49.5, and 1000 s are shown in Fig. 14. Comparing it with Fig. 7, it can be concluded that the two temperature change rules are similar. With an increase in hardfacing time, the temperature rises gradually and reaches the peak at 20 s (the moment for the ending of hardfacing). Moreover, during hardfacing (0–20 s), the temperature gradient before the heat source was sharp, while that behind the heat source was gentle. After hardfacing, the highest temperature area gradually moved toward the center, and the temperature of each area was basically the same when the hardfacing systems were completely cooled (1000 s). The temperature difference between Cr5Mo1V alloy and Cr5Mo1V-RE alloy at each time was very small, which can be ignored.

Figure 15 indicates the stress fields for Cr5Mo1V-RE alloy hardfacing models at 1.2, 6, 15, 20, 49.5, and 1000 s. From it, with an increase in hardfacing time, the peak stress increased and the stress area extended constantly. When the hardfacing system was cooled completely, the stresses were always focused on the HAZs. When the times were 1.2, 6.2, 14.8, 20, 49.5, and 1000 s, the peak stresses were 231.9, 358.0, 389.9, 403.8, 466.7, and 512.5 MPa, which are smaller than those for the Cr5Mo1V alloy hardfacing models.

Figure 16 indicates the longitudinal stress $\sigma_y$ and transverse stress $\sigma_x$ distribution along the hardfacing alloy centerline for Cr5Mo1V-RE alloy hardfacing models after the hardfacing system was cooled completely. From it, similar to those for the Cr5Mo1V alloy hardfacing models, the longitudinal stress $\sigma_y$ is coupled by tensile stress ($\sigma_y > 0$ MPa) and compressive stress ($\sigma_y < 0$ MPa) and the transverse stress $\sigma_x$ is tensile stress ($\sigma_x > 0$ MPa). The stress in the central zone is stable.
while that in the fringe areas fluctuate. What is more, for Cr5Mo1V-RE alloy, the peak values of $\sigma_y$ and $\sigma_x$ are 96 and 121 MPa, only 0.5 and 0.8 of those for Cr5Mo1V alloy, which indicates that the weldability of Cr5Mo1V-RE alloy is greater than of Cr5Mo1V. Moreover, the decreasing of $\sigma_y$ and $\sigma_x$ can both contribute on the decrease in the hardfacing stress for Cr5Mo1V-RE alloy, in which like here, the decline of the longitudinal stress $\sigma_y$ plays the major role.

Influence of Hardfacing Velocity on the Thermal and Stress Fields for Cr5Mo1V-RE Alloy

The thermal fields and stress fields for the Cr5Mo1V-RE alloy hardfacing models with hardfacing velocities of 3, 5, and 7 mm/s, in which the hardfacing times are 2, 1.2, and 0.86 s to make sure that the welding heat sources are at the same positions. From them, the hardfacing alloys are under the condition of melting, so the stress is 0 MPa. The large stresses are always focused on HAZs. Moreover, with an increase in the distance to hardfacing alloy centerline, the stress gradually decreased. For the different hardfacing velocities, although the distributions of initial stress were similar, there were large differences between the peak stresses, in which when the hardfacing velocity was 3 mm/s, the peak stress was 270.26 MPa, when the hardfacing velocity increased to 5 mm/s, it decreased to 231.9 MPa, and when the hardfacing velocity was 7 mm/s, the peak stress was lowest at 190.87 MPa.

Figure 18 shows the initial stress fields for the hardfacing models with hardfacing velocities of 3, 5, and 7 mm/s, in which the hardfacing times are 2, 1.2, and 0.86 s to make sure that the welding heat sources are at the same positions. From them, the hardfacing alloys are under the condition of melting, so the stress is 0 MPa. The large stresses are always focused on HAZs. Moreover, with an increase in the distance to hardfacing alloy centerline, the stress gradually decreased. For the different hardfacing velocities, although the distributions of initial stress were similar, there were large differences between the peak stresses, in which when the hardfacing velocity was 3 mm/s, the peak stress was 270.26 MPa, when the hardfacing velocity increased to 5 mm/s, it decreased to 231.9 MPa, and when the hardfacing velocity was 7 mm/s, the peak stress was lowest at 190.87 MPa.

Figure 19 illustrates the stress fields for the hardfacing models with different hardfacing velocities after the hardfacing systems were cooled completely. The stresses on the HAZs were large. Moreover, when the hardfacing velocity was 3 mm/s, the peak stress was 520.8 MPa and the stresses on most zones were larger than 165.8 MPa. When the hardfacing velocity increased to 5 mm/s, the peak stress was 512.5 MPa, while on most zones, the stresses were smaller than 128.6 MPa. When the hardfacing velocity further increased to 7 mm/s, the peak stress decreased to 488.6 MPa. Except for the hardfacing alloys and HAZs, the stresses on other zones were smaller than 89.2 MPa. With an increase in hardfacing velocity, the peak stresses at the cold state were not quite different, but the stress-influenced areas were quite discrepant.

Therefore, the hardfacing velocity influenced the peak stress at the hardfacing initial state and the stress-influenced areas at cold state. The larger the hardfacing velocity, the smaller the peak stress at cold state and smaller was the stress-influenced area at the cold state.

Preheating Temperature for Cr5Mo1V-RE Alloy

To investigate the influence of preheating temperature on the thermal and stress fields, the Cr5Mo1V-RE alloy hardfacing models were preheated to 0°, 50°, 100°, and 150°C before hardfacing, and then the thermal fields and stress fields were compared.
to each other. The hardfacing velocity was set to 5 mm/s.

Figure 20 indicates the thermal fields for Cr5Mo1V-RE alloy hardfacing models with different preheating temperatures at the hardfacing initial state (1.20 s). As the preheating temperature was 0°C, the peak temperature was 1570.1°C. With an increase in preheating temperature, the peak temperature rose slightly to 1598.5°C, 1647.6°C, and 1695.2°C when the preheating temperatures were 50°C, 100°C, and 150°C. Figure 21 shows the thermal fields for the hardfacing models with different preheating temperatures at the hardfacing middle state (10.2 s). As shown, when the preheating temperature increased from 0°C to 150°C, the peak temperature rose from 1927.8°C to 2035.1°C. Moreover, because the rising temperatures were not obvious, there were no obvious changes to the HAZs.

The stress fields for Cr5Mo1V-RE alloy hardfacing models with different preheating temperatures at 1.20 s are given in Fig. 22. When the preheating temperatures were 0°C, 50°C, and 100°C, the peak stresses were 231.9, 236.4, and 228.2 MPa, respectively. The differences among them were very small. However, when the
preheat temperature increased to 150°C, the peak stress decreased to 152.8 MPa, which is much smaller than those when the preheat temperatures were 0°, 50°, and 100°C. It can be concluded that when the preheat temperature is less than 150°C, the influence of preheating on the residual stress is very small, while when the preheat temperature increases to 150°C, the residual stress decreases drastically. Moreover, when the preheating temperature increased, the stress-influenced areas had little change. Figure 23 shows the stress fields for Cr5Mo1V-RE alloy hardfacing models with different preheating temperatures after the hardfacing systems were cooled completely, in which neither the peak stress nor the stress-influenced areas had obvious change.

Therefore, the preheating temperature only influences the peak stress at the hardfacing initial state. When the preheat temperature increased to 150°C, the residual stress decreases drastically. Therefore, in the actual production process, the matrix metals can be preheated (larger than 150°C) to decrease the hardfacing initial stress and avoiding cracking.

2. With an increase in hardfacing time, the temperature increases gradually. Temperature gradient before the heat source is sharp while that behind the heat source is gentle. On cooling, the highest temperature area moves toward the center. From hardfacing to cooling, the stress increases constantly. At the cold state, the large stresses are always focused on the HAZs.

3. For Cr5Mo1V-RE alloy, when the hardfacing times are 1.2, 6.2, 14.8, 20, 49.5, and 1000 s, the peak stresses are 231.9, 358.0, 389.9, 403.8, 466.7, and 512.5 MPa, which are smaller than those for Cr5Mo1V alloy, which indicates that the weldability of Cr5Mo1V-RE alloy is greater than that of Cr5Mo1V. The decrease of $\sigma_y$ and $\sigma_x$ can contribute to the decrease of the stress for the Cr5Mo1V-RE alloy, in which the decline of the longitudinal stress $\sigma_y$ plays a major role.

4. The hardfacing velocity influences the peak stress at the hardfacing initial state and the stress-influenced areas at the cold state. The larger the hardfacing velocity, the smaller is the peak stress at the cold state and the smaller is the stress-influenced area at the cold state.

5. The preheating temperature only influences the peak stress at the hardfacing initial state. When the preheat temperature is less than 150°C, the influence of preheating on the residual stress is small; however, when the preheat temperature increases to 150°C, the residual stress decreases drastically.

**References**


7. Yang, K., Zhang, Z. X., Hu, W. Q., Bao,


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**Fig. 19** — Stress fields for CrMo1V-RE alloy hardfacing models with different hardfacing velocities at cold state (1000 s): A — 3 mm/s; B — 5 mm/s; C — 7 mm/s.

**Fig. 20** — Thermal fields for CrMo1V-RE alloy hardfacing models with different preheating temperatures at hardfacing initial state (1.20 s): A — 0°C; B — 50°C; C — 100°C; D — 150°C.
Fig. 22 — Stress fields for Cr5Mo1V-RE alloy hardfacing models with different preheating temperatures at hardfacing initial state (1.20 s): A — 0°C; B — 50°C; C — 100°C; D — 150°C.

Fig. 21 — Thermal fields for Cr5Mo1V-RE alloy hardfacing models with different preheating temperatures at hardfacing middle state (10.2 s): A — 0°C; B — 50°C; C — 100°C; D — 150°C.
Fig. 23 — Stress fields for Cr5Mo1V-RE alloy hardfacing models with different preheating temperatures at cold state (1000 s): A — 0°C; B — 50°C; C — 100°C; D — 150°C.