

Numerical simulation of the effects of post-weld heat treatment on residual stresses in G20Mn5 cast steel welded joints

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Abstract: Post-weld heat treatment (PWHT) is widely used to mitigate residual stresses (RSs) in welded steel structures. However, existing studies have often reported PWHT outcomes without providing detailed mechanistic analyses of stress evolution during the thermal cycle, particularly for geometrically complex cast steel joints. To address this gap, this study investigated the G20Mn5-Q355 cast steel girth butt weld, employing a numerical simulation to dissect the RS evolution throughout the PWHT process. The model, validated against a five-pass arc welding procedure and code-compliant PWHT parameters, revealed that PWHT reduces peak axial and hoop RS by over 90%. The key innovative finding was that stress relaxation was highly stage-dependent—the heating stage alone accounted for nearly 75% of the total reduction, driven by material softening and creep effects. Furthermore, parameter analysis demonstrated that the holding temperature predominantly controls the final extent of RS reduction, whereas the heating rate influences the rate of relaxation. These insights offer a fundamental understanding of the PWHT mechanism and provide guidance for optimizing industrial procedures by prioritizing heating stage parameters to enhance efficiency.

Key words: cast steel welded joints; welding residual stresses; post-weld heat treatment; numerical simulation; creep effect

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The construction of large-scale infrastructures has driven the development of high-strength, heavy-

duty steel structures. Compared with conventional low-carbon steel components, cast steel joints provide superior design flexibility for complex connections, making them essential in large-span architectures, marine platforms, and bridges^[1-2]. Their integral casting eliminates intersecting welds, thereby significantly reducing stress concentrations at junctions^[3]. However, cast steel girth welds often involve unequal-thickness transitions and are susceptible to welding defects, making effective management of post-weld residual stress (RS) essential^[4-5].

RS adversely affects the dimensional accuracy, mechanical properties, and fatigue characteristics of welded components^[6-8]. Thus, the study of measurement, calculation, and control methods for RS remains critical in welding process optimization^[9]. Although process control is preferred because of efficiency and cost considerations^[10-11], welding complexities often necessitate post-weld treatments. In this regard, various thermal and mechanical techniques have been developed to introduce beneficial compressive stresses. For instance, Coules et al.^[12] showed that high-pressure rolling can transform RS into compressive stresses. Li et al.^[13] analyzed RS in 2.25Cr-1Mo pipes using a coupled thermal-metallurgical-mechanical model. Foehrenbach et al.^[14] efficiently predicted RS from ultrasonic impact treatment via finite element simulation, noting compressive stresses reaching substrate yield strength.

Cast steel girth butt welds exhibit a distinct RS profile due to geometric asymmetry from unequal wall thicknesses. Unlike the symmetric stress distribution in conventional plate joints, these welds develop axial compression on the outer surface and tension on the inner surface^[15-16]. This “outer compression-inner tension” configuration renders traditional surface-based mechanical treatments (e.g., hammer peening and shot peening) ineffective because they cannot reach the critical tensile zone inside. Consequently, post-weld heat treatment

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(PWHT) remains the primary method for relieving stress in such joints. Previous studies have confirmed PWHT's effectiveness in stress relief. For example, Dong et al.^[17] highlighted the dominant role of creep in RS elimination in P91 steel. Meanwhile, Sadeghi et al.^[18] reported reductions in strength, hardness, and RS in dissimilar steel joints after PWHT. Zhang et al.^[19] optimized the heating strip width for stress relief in unequal-thickness joints. Collectively, these works demonstrate PWHT's ability to alter RS and properties through creep formation, microstructural refinement, and thermal optimization. However, they mostly focus on phenomenological outcomes or specific materials without systematically analyzing coupled creep-thermal interactions governing RS evolution in complex cast steel joints. Given the pronounced RS gradients in these joints, a systematic numerical investigation into RS evolution and PWHT optimization is warranted^[20].

To address this gap, this study introduces a comprehensive numerical-experimental framework to elucidate the intricate thermomechanical mechanisms underlying PWHT in G20Mn5-Q355 cast steel welded joints. Using Abaqus and a thermal-elastoplastic framework, this research simulates both the welding and PWHT processes. The key innovation of this work lies in the detailed analysis of the RS field's evolution before and after heat treatment, focusing on how PWHT parameters influence stress reduction through the coupled effects of creep and thermal cycles. The proposed approach not only validates prior findings on stress relief mechanisms but also provides novel mechanistic insights for optimizing PWHT parameters to enhance the structural integrity of cast steel connections.

1 Simulation of a Heat Transfer Process in Joint Welding

1.1 Establishment of a finite element model for welded joints

A three-dimensional finite element (FE) model of a single-V groove butt-welded cast steel joint was developed in Abaqus using a DFLUX subroutine (Fig. 1) to obtain welding deformation and RS distribution for subsequent heat treatment analysis. The joint comprised a G20Mn5 cast steel pipe (wall thickness $T = 32$ mm) and a Q355 low-alloy steel pipe ($t = 16$ mm), with both sharing a diameter of $d = 219$ mm. The weld configuration included a 60° groove angle and a 4 mm root gap to ensure full penetration. Tables 1 and 2 present the chemical compositions and mechanical properties of both materials, primarily composed of ferrite and pearlite. A mesh sensitivity analysis was performed to balance between computational accuracy and efficiency. The adopted strategy employed a refined mesh near the weld and heat-affected zone (HAZ) to capture steep field gradients, transitioning to a coarser mesh in remote regions. This approach was verified to produce mesh-convergent results for RS.

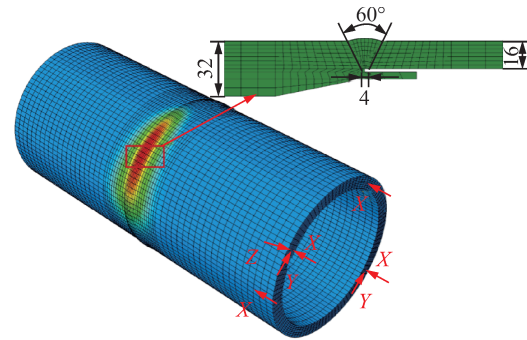


Fig. 1 FE model of the specimens (unit: mm)

Table 1 Chemical compositions of Q355 and G20Mn5 steel

Chemical element	C	Si	Mn	P	S	Ni	Cr	Mo	V	Cu	Al	Fe
G20Mn5	0.196	0.419	1.530	0.012	0.017	0.027	0.029	0.019	0.001	0.029	0.033	Bal.
Q355	0.150	0.650	1.470	0.012	0.013	0.007	0.034	0.008	0.003	0.029	0.000	Bal.

Table 2 Mechanical performance parameters of the studied materials

Material	Yield strength/MPa	Tensile strength/MPa	Elongation after fracture/%
G20Mn5	≥ 300	500-650	≥ 22
Q355	≥ 355	470-630	≥ 22

Experimental data were obtained from Ref. [21]. Gas-shielded welding was conducted at a speed (v) of 8.23 mm/s, with a voltage (U) of 26 V and a current (I) of 235 A, resulting in a thermal efficiency (η) of 0.8. Because of the substantial thickness of the specimen, a multilayer and multipass welding technique was employed, comprising a total of five welding passes.

Upon welding completion, the workpiece was allowed to cool to room temperature on the workbench. Thereafter, RS was measured using the hole-drilling technique.

The numerical simulation of the welding process was established using the thermoelastic-plastic FE method, which necessitated accounting for the thermophysical and thermomechanical properties of the weldment at various

temperatures, with specific parameters detailed previously^[22]. It is assumed that the properties of the filler metal are consistent with those of Q355.

1.2 Calculation of the joint temperature field and stress field

The temperature field calculation requires the definition of a heat source model. For the manual arc welding of the cast steel joint, a double ellipsoid heat source was used, comprising two distinct quarter-ellipsoids at the front and rear. The front quarter-ellipsoid is expressed as

$$q(x, y, z, t) = \frac{6\sqrt{3} f_f \Phi}{\pi^{3/2} a_f b c} \exp\left(-\frac{3}{a_f^2} x^2 - \frac{3}{b^2} y^2 - \frac{3}{c^2} z^2\right) \quad (1)$$

The back 1/4 ellipsoid is represented as

$$q(x, y, z, t) = \frac{6\sqrt{3} f_r \Phi}{\pi^{3/2} a_r b c} \exp\left(-\frac{3}{a_r^2} x^2 - \frac{3}{b^2} y^2 - \frac{3}{c^2} z^2\right) \quad (2)$$

where f_f and f_r denote the energy fractions of the front and back parts of the ellipsoid, respectively. $f_f + f_r = 2$, $f_f = 2/3$, $f_r = 4/3$. The heat source model was compiled using the DFLUX subroutine and called in Abaqus to realize the movement of the heat source during welding.

The welding simulation followed a sequentially coupled approach, using analogous meshing for thermal and mechanical analyses. Thermal analysis, conducted using DC3D8 elements, simulated heating and cooling stages, with the resulting temperature field applied as a load in the subsequent mechanical analysis using C3D8 elements. Mechanical boundary conditions (Fig. 1) were constrained only to prevent rigid-body displacement.

1.3 Temperature field and stress field results

Fig. 2 shows the thermal cycles of the joint. The welding process generates a highly localized and nonuniform temperature field, with peak temperatures occurring at the heat source center during arc movement. During cool-

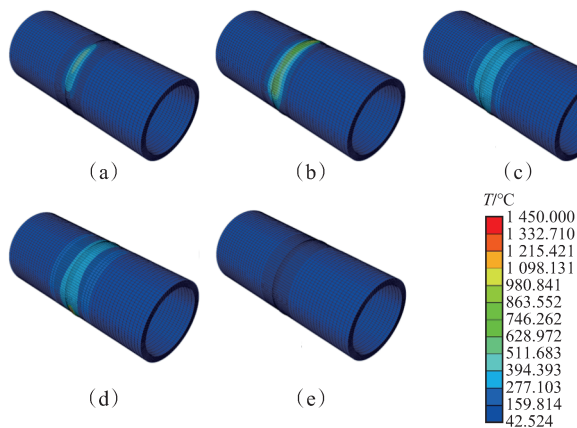


Fig. 2 Welding heat cycle history. (a) $t=20$ s; (b) $t=100$ s; (c) $t=200$ s; (d) $t=300$ s; (e) $t=2000$ s

ing, heat dissipates to the surroundings, reducing the temperature gradients until the pipe nears room temperature after 2000 s. The weld and HAZ experience rapid heating and cooling, while structural and material differences between the base metals cause asymmetric thermal responses, contributing to complex RSs and deformations that influence joint mechanical properties.

Fig. 3 presents the axial and hoop RS distributions, indicating significant stress gradients concentrated near the weld seam and HAZ. Peak stresses are observed at the weld start/stop locations and the pipe center, the latter due to pronounced thermal variations, reaching 362 and 426 MPa—exceeding the base metal yield strength. Stresses diminish away from the weld. Validation using the hole-drilling technique^[21] (red box in Fig. 3) confirms strong consistency with FE results, establishing reliability for subsequent analysis.

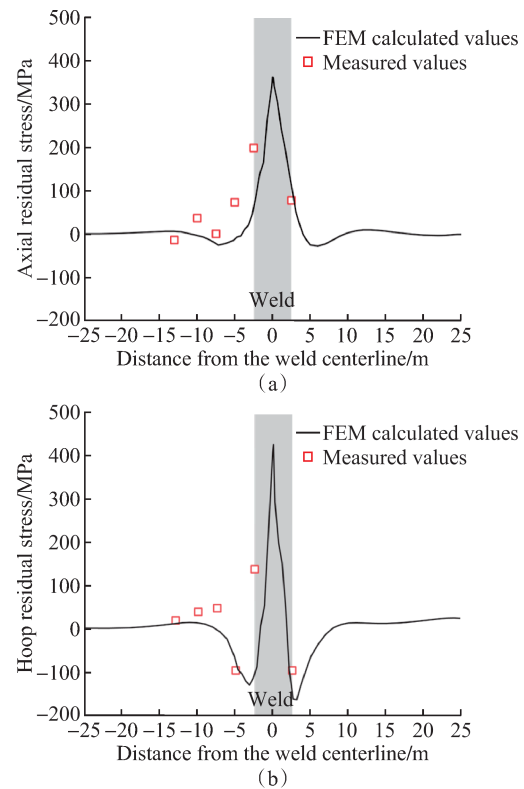


Fig. 3 Post-weld RS distribution. (a) Axial stress; (b) Hoop stress

2 Simulation of PWHT Processes

2.1 RS reduction mechanism by PWHT

PWHT reduces RS through two primary mechanisms^[17,23]: (1) high-temperature softening, where heating lowers a material's Young's modulus and yield strength, inducing plastic deformation; (2) creep deformation under sustained stress at elevated temperatures. PWHT simulations must incorporate both effects: temperature-dependent mechanical properties for softening and a constitutive model for creep.

Creep, defined as time-dependent plastic deformation under high temperature and stress, is negligible during rapid welding thermal cycles but essential in prolonged PWHT. As shown in Fig. 4, metallic creep typically progresses through three stages^[24]: instantaneous creep with initially high but decaying strain rate, steady-state creep with balanced hardening and recovery, and accelerated creep leading to fracture as internal damage accumulates.

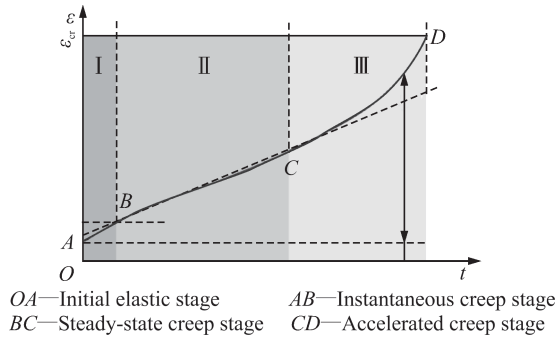


Fig. 4 Creep curve of metal materials

According to research, the numerical simulation results of PWHT are not significantly influenced by the choice of the creep model type^[17]. In this study, the commonly used Field & Field model was employed to characterize the creep behavior of steel in the PWHT simulation:

$$\varepsilon_c = a\sigma^b t^c \quad (3)$$

where ε_c is the creep strain; σ is the equivalent stress; t is the creep time; and a , b , and c are temperature-dependent material parameters. The values of the parameters used in this paper are from Ref. [25] and are shown in Table 3. Given the comparable chemical compositions and room-temperature mechanical properties of G20Mn5 and Q355, the creep model of Q355 steel was applied to the entire joint in the absence of published high-temperature creep parameters for G20Mn5 cast steel. The creep properties are given by writing a Creep subroutine in the FORTRAN language.

Table 3 Creep model parameters^[25]

Temperature/°C	a	b	c
400	5.09×10^{-23}	7.357 87	0.415 35
450	5.64×10^{-23}	7.490 26	0.580 97
500	1.86×10^{-24}	8.323 15	0.768 55
550	1.07×10^{-21}	7.396 08	0.901 20
600	2.58×10^{-19}	6.686 47	0.943 01
700	2.78×10^{-15}	3.352 97	0.999 90

PWHT consists of three stages: temperature rise, holding, and cooling. This necessitates the careful design of the holding PWHT temperature (T_{PWHT}), holding time (t_{hold}), and heating rate (v_{heat}) (Fig. 5). To ensure the

appropriate heat treatment temperature field, these parameters are established following the CECS 330—2013 code^[26]: heating to 600 °C at a rate of 5 °C/min for 2 h, followed by cooling to room temperature within the furnace.

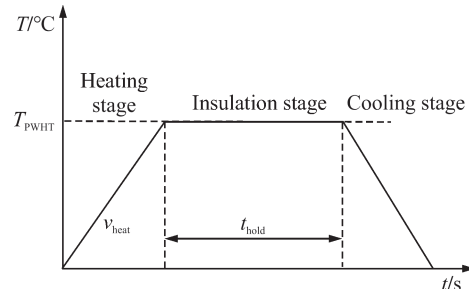


Fig. 5 Definition of PWHT parameters

The welding-simulated RS field served as the initial state for subsequent PWHT analysis using the same FE model. Given the slow heating and cooling rates during PWHT, a uniform temperature distribution was assumed throughout the weldment. The thermal cycle was applied directly to node temperatures, with C3D8T elements employed for fully coupled thermomechanical analysis under consistent mechanical boundary conditions (Fig. 6).

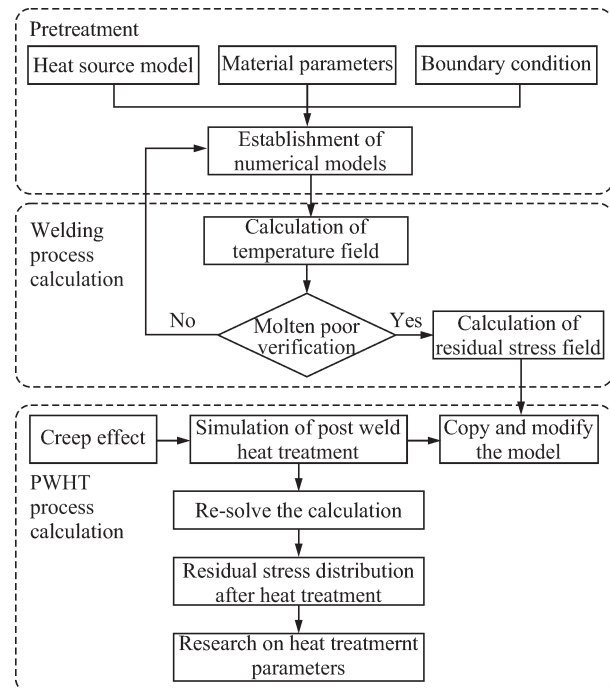


Fig. 6 Flow chart of PWHT simulation calculation

2.2 Calculation results

To analyze RS evolution during PWHT, axial and hoop stresses at the weld were tracked over time (Fig. 7). During initial heating, RS decreased rapidly and nearly linearly as the temperature rose because of material yield strength reduction and plastic strain accumulation. As the temperature further increased, creep strain

accelerated. Once the target T_{PWHT} was reached, RS reduction slowed as creep strain stabilized and material softening stabilized. During cooling, RS partially rebounded owing to elastic modulus recovery but remained below 50 MPa.

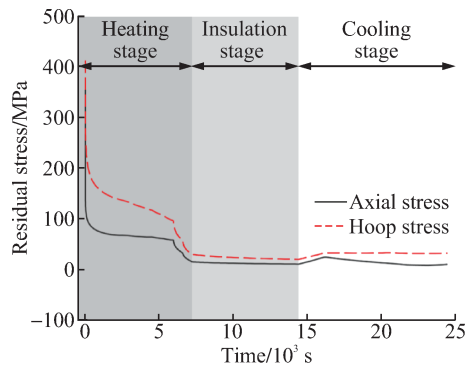


Fig. 7 Reduction of RS during PWHT

Fig. 8 shows the evolution of elastic, plastic, and creep strains at the weld seam during PWHT. During heating, rising temperature reduced both yield strength and Young's modulus, causing elastic and plastic strain to decay rapidly in the initial phase. After about 1 h, creep strain grew markedly but stabilized upon reaching the target PWHT temperature, showing little change during holding. During cooling, elastic strain fluctuated slightly owing to recovering material stiffness, whereas plastic and creep strains remained nearly constant. Overall, material softening, creep, and property changes are essential drivers of RS relief.

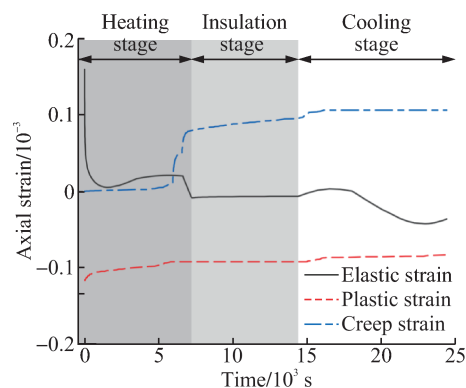


Fig. 8 Variation in elastic, plastic, and creep strains of welds with time during heat treatment

Fig. 9 illustrates the distribution of RS along the vertical direction of the weld seam after PWHT. The RS distribution trends before and after PWHT were relatively similar. However, following PWHT, the peak values of axial and hoop RSs were significantly reduced, resulting in a more uniform stress distribution. Specifically, the peak axial RS decreased from 362 to -15 MPa, whereas the peak hoop RS decreased from 426 to 20 MPa, yield-

ing a reduction ratio of over 90%. This demonstrates that the PWHT process effectively reduces post-weld RS.

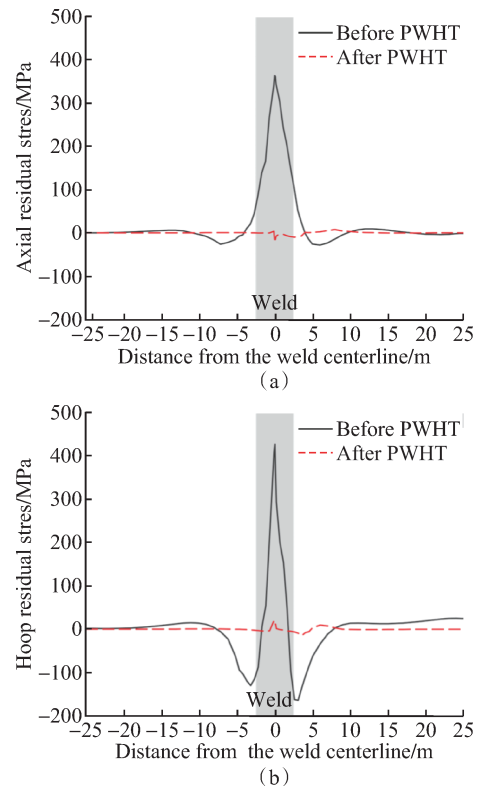


Fig. 9 Variation of RS before and after PWHT. (a) Axial RS; (b) Hoop RS

3 Analysis and Discussion of Results

3.1 Influence of softening and creep effects

To clarify the control mechanisms of RS reduction during PWHT, this study quantitatively analyzed the roles of material softening and creep. Four FE models were developed (Table 4): EXPA ignored both effects; EXPB and EXPC considered only softening or creep, respectively; and EXPD incorporated both.

Table 4 PWHT simulation example

Example	Softening effect	Creep effect
EXPA	N	N
EXPB	Y	N
EXPC	N	Y
EXPD	Y	Y

The four simulation cases were compared with the as-welded condition (no PWHT). Fig. 10 shows the axial RS contours. Cases in Figs. 10(a) and (b) illustrate that neglecting softening and creep results in higher near-weld RS. Cases in Figs. 10(c) and (d) demonstrate that including these effects significantly reduces the peak RS by 206 and 226 MPa, confirming their critical role in stress relaxation. Whereas the first four cases showed

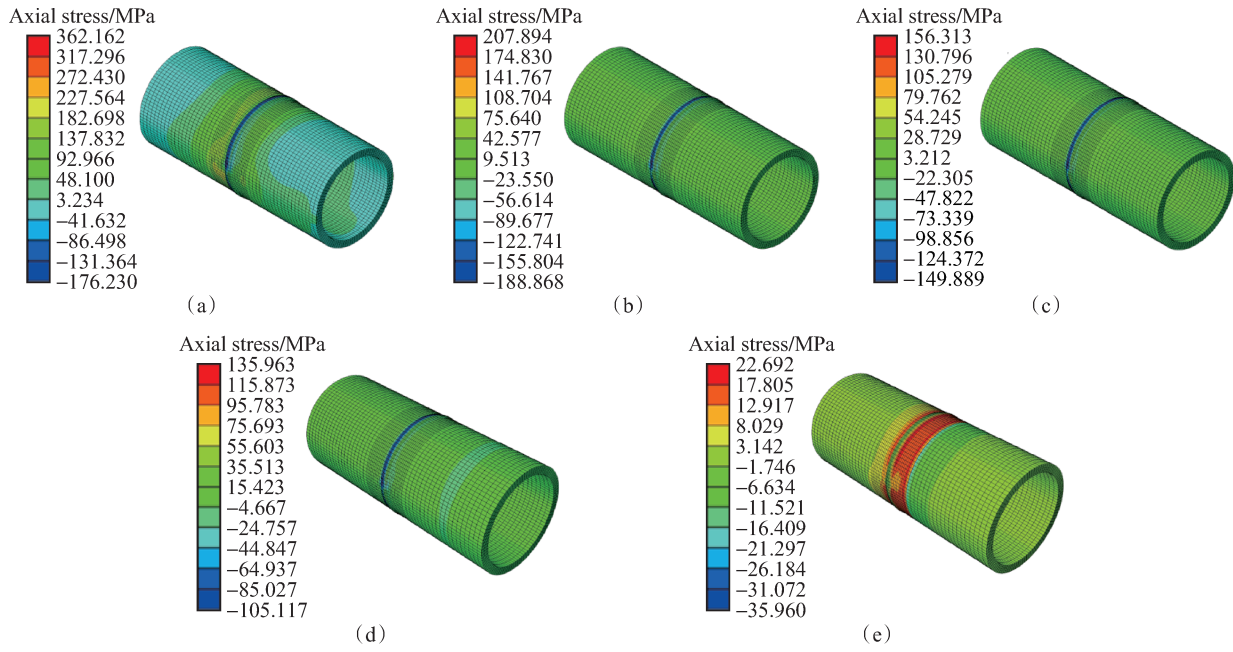


Fig. 10 Results of axial RS obtained for different examples. (a) Without heat treatment; (b) EXPA; (c) EXPB; (d) EXPC; (e) EXPD

consistent “outer compression-inner tension” patterns decaying with distance from the weld, the simultaneous consideration of softening and creep altered this distribution (Fig. 10(e)). This combined approach not only reduced peak weld stresses but also induced partial stress reversal, yielding a more uniform and significantly relieved RS state in the EXPD case.

3.2 Effects of PWHT parameters

The effects of three PWHT parameters (T_{PWHT} , t_{hold} , and v_{heat}) on stress relief were analyzed. Fig. 11 shows the RS evolution under different heating rates ($v_{heat} = 2.5\text{--}12.5\text{ }^{\circ}\text{C/min}$). RS dropped rapidly during heating, stabilized during holding, and slightly rebounded upon cooling. Although v_{heat} accelerated RS reduction during heating, it had little effect on the final stress level. Higher v_{heat} improved efficiency but risked uneven heating, potentially introducing new RS. Fluctuations in RS evolution stemmed from interactions among elastic, plastic, and creep strains, as explained in Section 2.2.

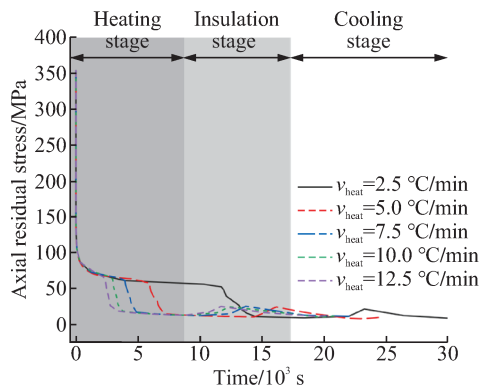


Fig. 11 Effect of v_{heat} on residual stress

Fig. 12 shows the influence of T_{PWHT} ($450\text{--}650\text{ }^{\circ}\text{C}$) on RS. Although the reduction trend resembled that in Fig. 11, the final RS varied considerably with temperature. Higher T_{PWHT} intensified material softening and creep, promoting plastic deformation and greater stress relief. Thus, increasing T_{PWHT} not only enhances stress reduction but also improves weld performance, suggesting its appropriate elevation for more effective RS control.

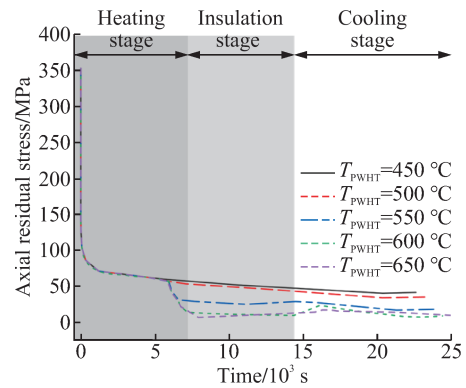


Fig. 12 Effect of T_{PWHT} on residual stress

Fig. 13 compares the RS evolution for holding times (t_{hold}) of 1 to 5 h. All curves followed similar trends, with only minor divergence during cooling. Extending t_{hold} had a negligible effect on RS reduction, consistent with prior findings that stress relief occurs mainly during heating, before reaching T_{PWHT} [17–18]. To improve efficiency, a shorter t_{hold} is recommended without compromising stress relief outcomes.

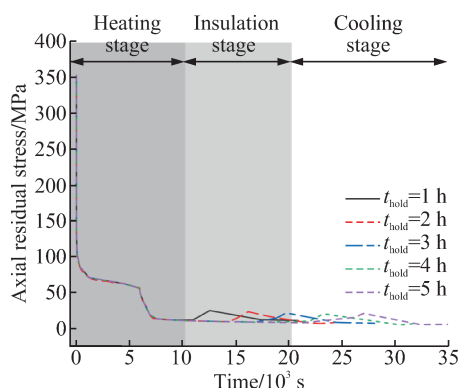


Fig. 13 Effect of holding time on residual stress

4 Conclusions

This study employed a thermoelastoplastic modeling approach in Abaqus to numerically investigate the evolution of RS during the PWHT of G20Mn5-Q355 cast steel girth welds. The efficiency of RS reduction under various PWHT parameters was systematically analyzed, leading to the following main conclusions:

(1) A significant stress gradient exists in the as-welded RS field, with peak axial and hoop stresses reaching levels near the material's yield strength (400-450 MPa) and concentrated in the weld and HAZ. PWHT effectively mitigates these stresses, reducing the peak values by over 90% to a final magnitude below 50 MPa.

(2) RS release is highly stage-dependent, with the heating stage contributing nearly 75% of the total reduction. This is mechanistically driven by the combined effects of metal softening (reduced yield strength) and accelerated creep strain accumulation. Material softening enables initial rapid relaxation, which is then sustained and enhanced by dominant creep deformation as temperature rises.

(3) Parametric analysis shows that the final RS reduction is predominantly controlled by the holding temperature, with higher temperatures (600-650 °C) enhancing creep-driven inelastic strain. The heating rate primarily influences the relaxation rate, while extending the holding time yields diminishing returns. Thus, optimization should prioritize achieving a sufficient holding temperature with a moderate heating rate rather than prolonged holding time.

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焊后热处理对 G20Mn5 铸钢焊接接头残余应力影响的数值模拟

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摘要: 焊后热处理(PWHT)可以有效地减轻钢结构焊接接头中的残余应力(RS),然而现有研究通常关注焊后热处理的最终结果,缺少对热循环过程中应力演变的详细机制分析,特别是对于几何形状复杂的铸钢接头。针对这一问题,本研究以 G20Mn5-Q355 铸钢接头环向对接焊缝为研究对象,利用数值模拟方法,分析了焊后热处理过程中残余应力的演化规律。焊接过程包括5道电弧焊,焊后热处理参数按照相关规范确定。结果表明:焊后热处理可将轴向和环向残余应力峰值降低90%以上;应力松弛主要发生在加热阶段,占总减小量的近75%,由材料软化和蠕变效应驱动。对工艺参数的分析表明,残余应力的消减程度主要受焊后热处理温度的影响,而消减速率受加热速率的影响。以上结论明确了焊后热处理对残余应力的消减机制,并建议优先考虑升高热处理温度来提高效率,为相关工艺优化提供了参考。

关键词: 铸钢焊接接头;焊接残余应力;焊后热处理;数值模拟;蠕变效应

中图分类号: TG404