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The Influence of Groove Geometry on the Creep Fracture Behavior of Dissimilar Metal Welds between Ferritic Heat-Resistant Steels and Nickel-Based Alloys

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Abstract: This study investigates the influence of groove geometry on the high-temperature creep life and fracture behavior of Dissimilar Metal Welds (DMWs) between low-alloy steel 2.25Cr1Mo and austenitic stainless steel 347H using Inconel 82 nickel-based filling metal. This research aims to reveal the effect of groove geometry, especially the stepped groove, on creep crack propagation path and creep life, through a combined approach of finite element simulation considering stress triaxiality and experimental validation. The study reveals that the stepped groove alters the creep crack propagation path, enhancing the endurance life by deflecting cracks away from the weld/heat-affected zone (HAZ) interface and directing them into regions with higher creep resistance. The experimental results verify the simulation findings, revealing that the stepped groove joints exhibited longer creep life with changes in failure location and mechanism compared to the V-groove joints. However, it was found that the stepped groove intensified the stress concentration at the early creep stage. Thus, a good balance should be achieved between the negative (stress concentration at interface) and positive (changing crack paths) effects of the stepped groove to extend the creep life of DMWs.



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Keywords: Dissimilar Metal Welds (DMWs); creep fracture; finite element methods; groove geometry; failure mechanism

1. Introduction

In power plant facilities, DMWs that connect ferritic to austenitic steels are commonly used. Numerous cases have indicated that such joints are prone to premature failure during service, leading to significant economic losses and safety risks for power plants [1].

The prevalent premature failure mechanisms mainly include Type IV failure occurring in the HAZ of ferritic heat-resistant steels and interfacial failure that occurs at the interface between weld and the HAZ of ferritic steels [2,3]. The Type IV failure mechanism involves microstructural and mechanical factors, such as the lack of sufficient precipitate pinning and high triaxial tensile stresses in the HAZ [4–7], whereas interfacial failure is related to the formation of Type I carbides at the interface [8], thermal stress, oxidation, and structural stress [6].

Recent studies have focused on the effects of the welding process [9], filler metal [10,11], and post-weld heat treatment [10,12] on the microstructure evolution and mechanical properties of DMWs. Vanaja et al. [13] investigated the creep rupture behavior of a DMW between 316LN stainless steel and Grade 91 steel fabricated by an electron beam. They found that the failure location shifted from the base metal to the inter-critical HAZ of Grade 91 steel after long-term creep exposure, but the weld interface exhibited good stability.

Singh et al. [14] and Santoso et al. [15] demonstrated that a buttering layer can effectively improve the creep strength of DMWs by accommodating the material property gradient near the interface.

Hyde et al. [16] reviewed the high-temperature creep analysis of pressurized circumferential pipe weldments, covering material properties, experimental testing, constitutive equations, and numerical modeling methods. They summarized the potential uses and limitations of finite element methods in predicting the stresses and failure behavior of pipe weldments. Parker et al. [17] conducted creep tests on conventional grooved and stepped groove joints of P91 steel homogenous metal welds, finding that a well-designed stepped groove could prolong the time between crack formation and failure by avoiding the coalescence of creep voids along the heat-affected zone, thereby increasing creep life. Building upon Parker's findings, this study aims to further investigate how the stepped groove geometry affects the creep fracture behavior and creep life of ferritic/nickel DMWs in order to provide guidance for groove design to delay the premature failure of DMWs in power plants.

In terms of creep damage modeling, current research mainly focuses on macroscopic phenomenological models based on stress, such as the Kachanov–Rabotnov model [18,19] and the Liu–Murakami (L-M) model [20]. These models are designed for homogeneous single materials and do not consider the influence of structural constraints on damage evolution; thus, they have limitations in terms of simulating creep damage in complex structures like DMWs [21]. Naumenko and Altenbach [22] proposed a phenomenological model to describe the anisotropic creep behavior in weld metal produced by multipass welding. They introduced a mechanical model for a binary structure composed of fine-grained and coarse-grained constituents with different creep properties. Their modeling results agreed qualitatively with the experimental observations and demonstrated the capability of the continuum damage mechanics approach for analyzing the creep strength of welded joints. Hayhurst et al. [23] performed three-dimensional creep continuum damage mechanics analyses on a welded branched pressure vessel using a five-material weld model. They accurately predicted the failure location, mode, and lifetime of the vessel. The importance of considering the material inhomogeneity across the weldment in creep damage modeling was highlighted. Goyal et al. [24] carried out the finite element analysis of Type IV cracking in 2.25Cr-1Mo steel weldment based on a micro-mechanistic approach. They estimated the stress and strain distributions across the weldment considering the micro-mechanical strength inhomogeneity. The results showed higher stresses in the inter-critical region of the heat-affected zone, leading to localized creep deformation and cavitation. The role of intergranular precipitates in facilitating creep damage was also analyzed. Wang et al. [25] simulated the creep failure process of a 9%Cr steel welded joint using the continuum damage mechanics method based on a modified Kachanov–Rabotnov constitutive equation. The damage evolution with increasing creep time was characterized. Honda et al. [26] recently developed a creep damage analysis scheme for Mod.9Cr-1Mo steel welds considering void mechanics modeling. The increase in the creep void density and its critical value for micro-crack initiation were modeled. The predicted void density distribution and failure process agreed well with the experimental results. Ragab et al. [27] established a multi-axial creep damage model for a Grade 91 steel welded joint under ultra-supercritical conditions. The damage distributions and cracking behavior predicted by the model correlated reasonably with the industrial observations. In a recent review, Ragab et al. [28] summarized the requirements and challenges of developing improved creep-ductility-based constitutive models for tempered ferritic/martensitic steels. The limitations of existing models and the need for incorporating microstructure-specific damage parameters were emphasized. Cano et al. [29] combined the Wilshire equations with continuum damage mechanics to create a new constitutive model capable of predicting the long-term creep deformation, damage, and rupture of P91 steel.

This study focuses on the DMWs between low-alloy steel 2.25Cr1Mo and austenitic stainless steel 347H using Inconel 82 nickel-based filling metal. An improved creep damage

model is proposed by introducing stress triaxiality into the L-M model, aiming to better describe the damage development in the structurally constrained regions near the dissimilar material interface. Considering the long duration and high cost of creep tests, a finite element simulation method was initially used to compare the effects of groove geometry on creep fracture behavior. Based on this, creep tests were conducted to further examine the validity of the simulation results.

Furthermore, DMWs were fabricated in the laboratory, and high-temperature creep tests were conducted. The joints were analyzed after failure to determine the failure location and mechanism. This research provides new insights into the role of groove geometry on DMWs' creep life and fracture modes, which can serve as valuable references for extending the creep life of DMWs in engineering applications.

2. Creep Damage Model

2.1. Development of the Improved Creep Damage Model

As previously mentioned, the L-M model is only applicable to homogeneous models of a single material and does not take into account the influence of structural constraints on creep damage; thus, it cannot accurately describe the creep damage in complex structures such as DMWs. Therefore, based on the L-M model and considering the structural characteristics of DMWs, this study makes improvements by introducing a triaxial stress variable and develops a new creep damage model.

The creep constitutive model of the L-M model can be expressed as follows:

$$\dot{\epsilon}_{cr} = A\sigma_{eq}^n \exp\left(\frac{2(n+1)}{\pi\sqrt{1+\frac{3}{n}}}D^{1.5}\right), \quad (1)$$

where $\dot{\epsilon}_{cr}$ is the creep strain rate, σ_{eq} is the von Mises equivalent stress, D is the damage variable, and A and n are the material parameters. The damage evolution equation of this model is as follows:

$$\frac{dD}{dt} = \frac{B(1 - \exp(-q))\sigma_f^p \exp(qD)}{q}, \quad (2)$$

where B , p , and q are the material parameters; σ_f is the damage equivalent stress, which is a function of the maximum principal stress σ_1 and the von Mises equivalent stress σ_{eq} , given by $\sigma_f = \alpha\sigma_1 + (1 - \alpha)\sigma_{eq}$, with α being a material parameter that equals 1 when the maximum principal stress dominates and 0 when the equivalent stress dominates. Considering the influence of structural constraints between different materials near the interface in DMWs on the development of creep damage, the equivalent stress σ_{eq} in Equations (1) and (2) is replaced with a variable that includes the triaxiality of stress. Considering the influence of structural constraints between different materials near the interface in DMWs on the development of creep damage, the equivalent stress σ_{eq} in Equations (1) and (2) is replaced with a variable σ_t that includes the stress triaxiality η . η is defined as the ratio of hydrostatic stress σ_m to von Mises equivalent stress σ_{eq} , namely $\eta = \frac{\sigma_m}{\sigma_{eq}} = \frac{\frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3)}{\sigma_{eq}}$, where σ_1 , σ_2 , and σ_3 are the three principal stresses. The physical meaning is that under the same equivalent stress, a higher η value represents a higher degree of stress constraint, which is more likely to cause creep void formation and promote creep damage [30]. The improved creep constitutive model can be expressed as follows:

$$\dot{\epsilon}_{cr} = A\sigma_t^n \exp\left(\frac{2(n+1)}{\pi\sqrt{1+\frac{3}{n}}}D^{1.5}\right), \quad (3)$$

$$\frac{dD}{dt} = \frac{B(1 - \exp(-q))\sigma_f^p \exp(qD)}{q}, \quad (4)$$

where $\sigma_t = 3\eta\sigma_{eq}$, and $\sigma_f = \alpha\sigma_1 + (1 - \alpha)\sigma_t$. In this study, the triaxiality η is calculated based on the stress state of the model.

2.2. Model Parameter Acquisition

The related parameters for each material in the DMW are all derived from the published literature [30–33], which is listed in Tables 1 and 2.

Table 1. Elastoplastic parameters of materials in different parts of the DMW model.

Material	Elastic Modulus E , GPa	Poisson's Ratio ν	Expansion Coefficient ¹ α , $10^{-5}/^{\circ}\text{C}$	Yield Strength σ_{YS} , MPa
WM ² (IN82)	190	0.3	1.570	240
ICHAZ ³ (2.25Cr1Mo)	176	0.3	1.406	170
CGHAZ ⁴ /BM ⁵ (2.25Cr-1Mo)	176	0.3	1.406	170

¹ The coefficients of thermal expansion in the table are measured based on a reference temperature of 25 °C. ² WM: weld metal. ³ ICHAZ: inter-critical heat-affected zone. ⁴ CGHAZ: coarse-grained heat-affected zone. ⁵ BM: base metal.

Table 2. Creep damage model parameters of materials in different parts of the DMW model.

Parameter	BM	CGHAZ	ICHAZ	WM
$A(\text{MPa}^{-n}\text{h}^{-1})$	2.91×10^{-9}	1.46×10^{-10}	1.55×10^{-8}	4.5×10^{-38}
n	3.1017	3.1017	3.1017	13.16
B	1.79×10^{-9}	1.79×10^{-9}	7.16×10^{-9}	2.05×10^{-37}
p	3.0248	3.0248	3.0248	14.361
q	3.46	3.46	3.46	3.46

2.3. Validity Verification of Proposed Model

To verify the accuracy of the improved model, it was compared with the L-M model, focusing on how each model describes the damage situation near the interface between IN82 weld metal and 2.25Cr1Mo base metal. A simple joint model was established to facilitate this comparison. Subsequently, the simulation results from both the L-M model and the improved model were compared.

2.3.1. Finite Element Model and Related Settings

The finite element model was established using the commercial software ABAQUS (version 2022), as shown in Figure 1. Firstly, the stress–strain field was calculated using the static, general analysis step, followed by the computation of creep behavior using the visco analysis step. A user-defined creep subroutine, CREEP, was developed based on the improved constitutive model to describe the creep behavior. The element type used in the model was CPE4R, which is a four-node bilinear plane strain quadrilateral element with reduced integration and hourglass control. For the simple joint model, the number of elements after meshing was 1000 for both the L-M model and the improved model. The damage evolution equation was integrated using an explicit scheme with automatic time step control to ensure convergence and accuracy.

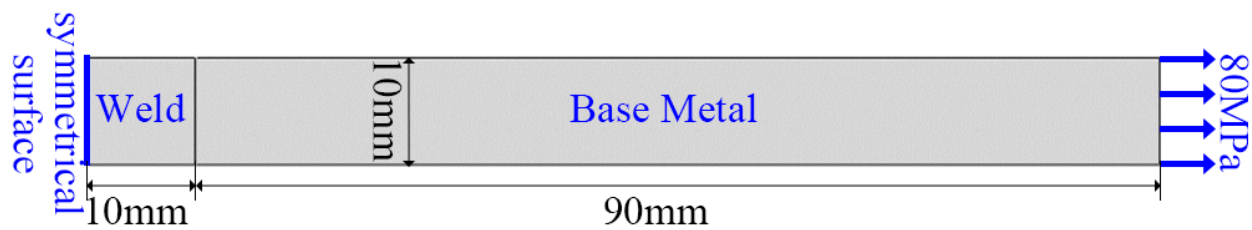


Figure 1. Finite element model of DMWs between ferritic heat-resistance steel and nickel-based weld metal.

2.3.2. Simulation Results and Analysis

The creep damage simulation results are shown in Figure 2. It can be seen that the creep damage in the improved model is mainly concentrated near the interface between the weld and the base metal, which is consistent with the common failure locations in actual DMWs. Therefore, the improved model can more realistically depict the creep damage in DMWs. In contrast, the simulation results from the L-M model show that the creep damage is concentrated in a larger area near the interface within the HAZ and the base metal, and the impact of the structure on the distribution of creep damage is not obvious. This qualitative comparison proves that the L-M model has limitations in depicting creep damage in complex structures, while the improved model, considering stress triaxiality, can better capture the damage localization near the interface of DMWs.

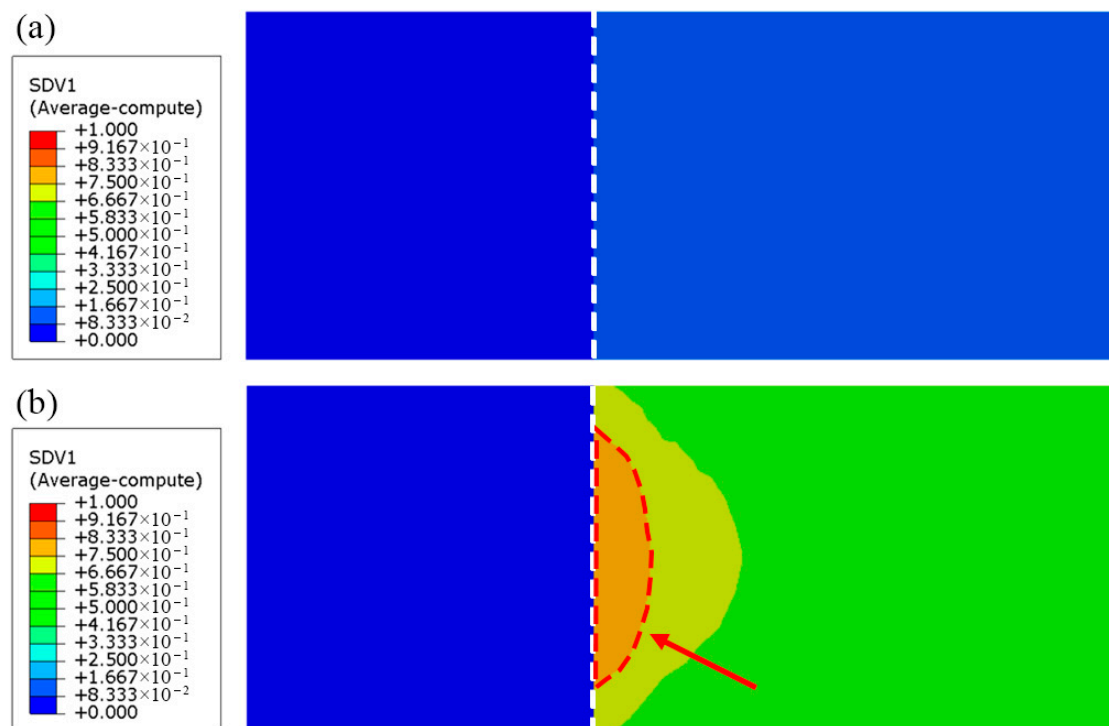


Figure 2. Contour map of damage variable for weld/heat-resistant steel ($t = 290.3$ h), where (a) is the simulation results based on the L-M model, and (b) is the simulation results based on the improved model (the dashed white line indicates the weld interface).

3. Simulation and Experiments

3.1. FEM Model

Finite element models of weld joints with V-groove and stepped groove configurations were established using ABAQUS, with the simulated creep temperature set at 580 °C. The boundary conditions were set to be fixed on one side and subjected to a load of 80 MPa on the other side, as shown in Figure 3. The base metals on both sides of the joint were

low-alloy steel 2.25Cr1Mo and austenitic stainless steel TP347H, respectively, and the filler metal was IN82 nickel-based alloy (ERNiCr-3). The chemical compositions of these three materials are listed in Table 3.

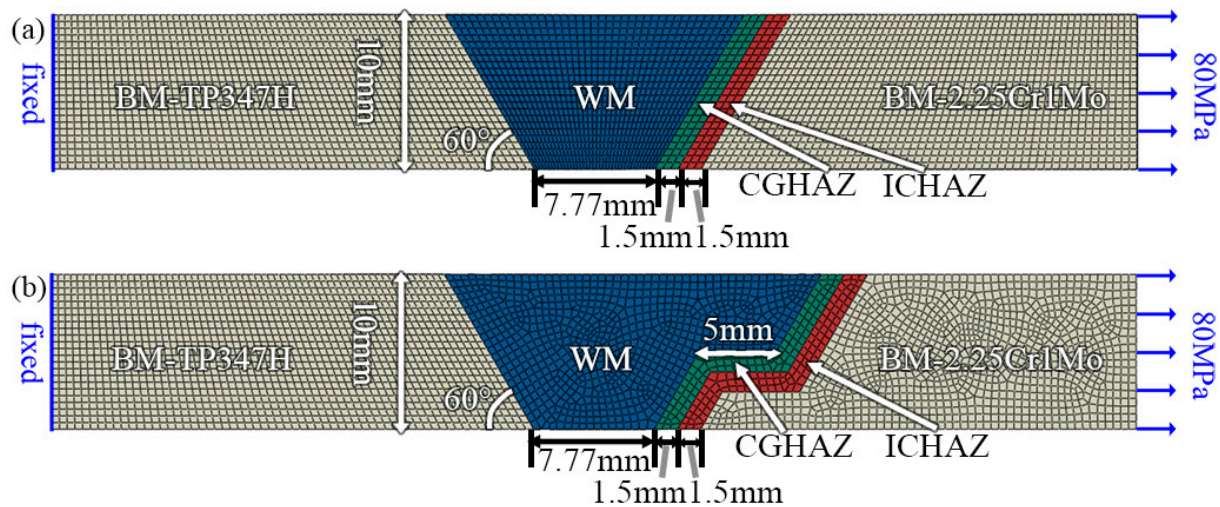


Figure 3. Finite element model.

Table 3. Chemical composition of base metals and welding wire (wt. %).

Element	Fe	Ni	Cr	Mo	Co	Al
IN82 (ERNiCr-3)	0.2	Bal.	20.4	-	0.03	-
BM-2.25Cr1Mo	Bal.	0.1	2.2	0.92	-	0.03
BM-TP347H	Bal.	9.07	19.4	0.29	-	-
Element	Nb	C	Si	Mn	Cu	Ti
IN82 (ERNiCr-3)	2.48	0.01	0.05	3.2	<0.01	0.37
BM-2.25Cr1Mo	<0.01	0.07	0.2	0.52	0.14	<0.01
BM-TP347H	0.68	0.05	0.44	1.75	0.15	-

The mesh size of the finite element model was approximately 0.5 mm, and the element type was C3D8T, which is an eight-node trilinear brick element for three-dimensional thermal analysis with full integration and temperature degrees of freedom. The number of elements after meshing was 44,988 for the V-groove joint model and 42,012 for the stepped groove joint model. A process of heating from 25 °C to 580 °C was first established to simulate thermal stress. Subsequently, a short analysis step was set up to calculate the stress–strain field, followed by the computation of the overall creep fracture process. The initial step size for the creep calculation analysis step was set to 10^5 h, with a minimum step size of 10^{-20} h and a maximum step size of 10 h. To prevent large displacements that could lead to non-convergence of the calculations, the geometric nonlinearity switch was turned on.

3.2. DMW Manufacturing

To verify the validity of the calculation results, high-temperature creep tests were also conducted on joints with the two groove geometries, as shown in Figure 4. The weld joints were manufactured using automatic tungsten inert gas welding. The welding parameters are listed in Table 4.

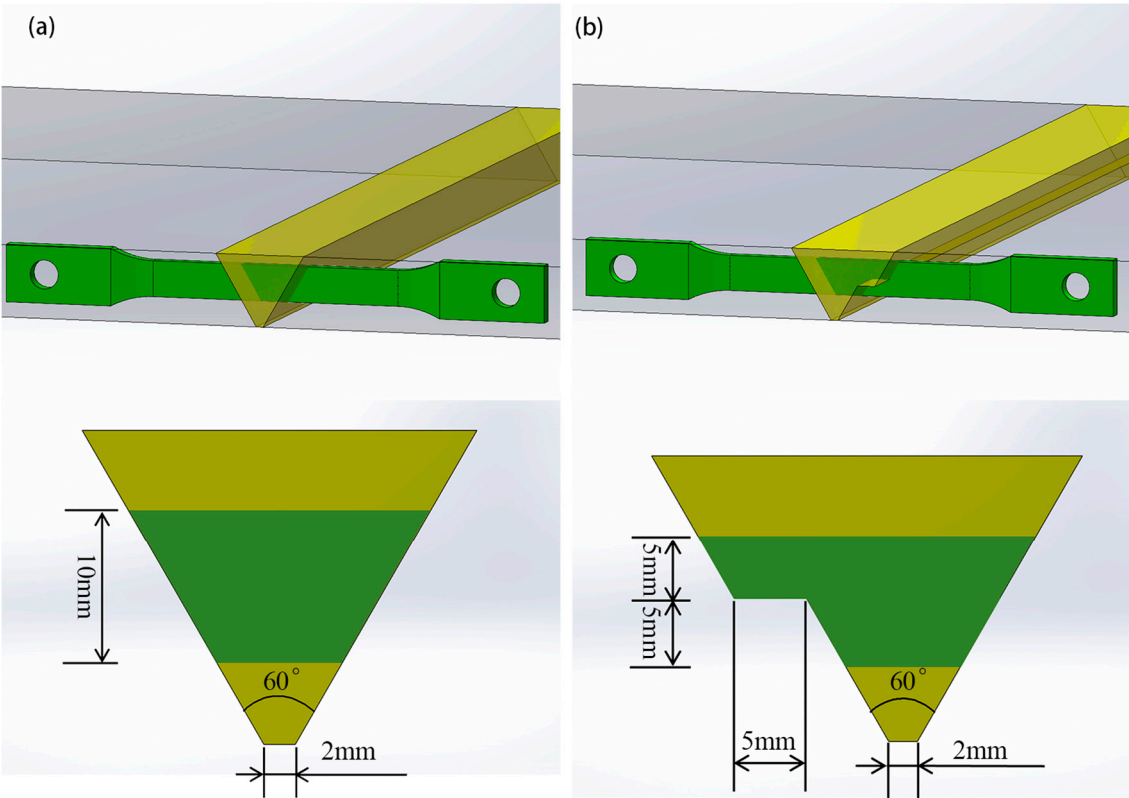


Figure 4. Schematic diagrams of joints with two groove geometries: (a) V-groove; (b) stepped groove.

Table 4. Welding process parameters.

Voltage (V)	Current (A)	Welding Speed (cm/min)	Wire Feed Speed (cm/min)	Wire Diameter (mm)	Shielding Gas	Gas Flow (L/min)
15	180	15	180	1.0	AR	8–10

After welding, the joints were subjected to PWHT (post-weld heat treatment) according to standard BS-2633-1987, and the temperature–time curve is shown in Figure 5.

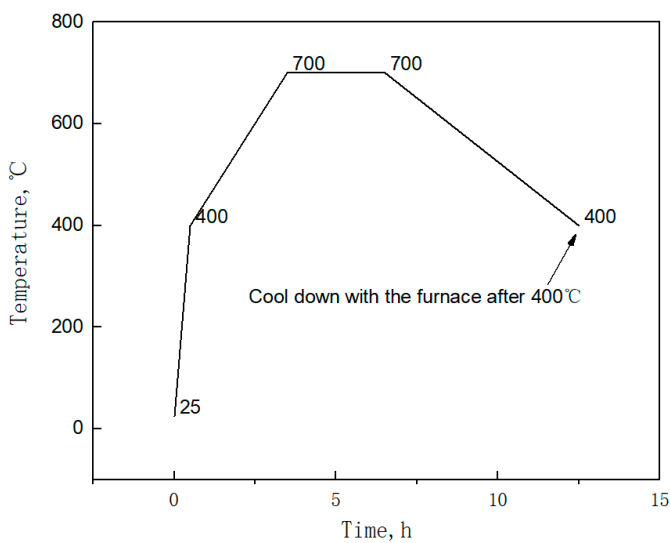


Figure 5. Temperature–time curve of PWHT.

3.3. Creep Tests and Microstructural Characterization

Creep specimens were extracted from the joint, as shown in Figure 4, and creep tests were conducted at 580 °C with a stress of 80 MPa. The dimensions of the specimens are shown in Figure 6. The tests were stopped when the specimen fractured.

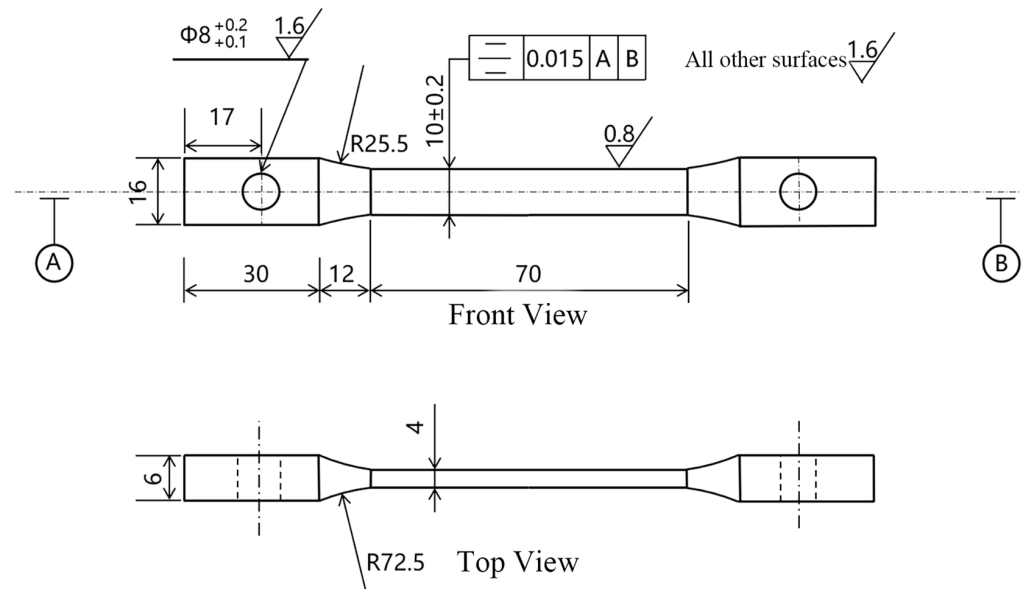


Figure 6. Schematic diagram of creep specimen dimensions.

After the fracture of the specimen, an optical microscope (OM) and a scanning electron microscope (SEM) were used to observe the microstructure in the vicinity of the fracture to determine the fracture location and the morphology of the microstructure. The optical microscope used was an Olympus CX14, manufactured by Olympus Corporation, Tokyo, Japan, and the scanning electron microscope was a TESCAN LYRA3, produced by TESCAN ORSAY HOLDING, Brno, Czech Republic. Considering the good positive correlation between Grain Reference Orientation Deviation (GROD) and material creep deformation [33–36], the Oxford Nordlys max3 equipment, manufactured by Oxford Instruments, Abingdon, UK, was used to analyze the area near the fracture, following vibratory polishing performed on the specimen surface to remove residual surface strains. The Electron Backscattered Diffraction (EBSD) scanning area was $120\ \mu\text{m} \times 120\ \mu\text{m}$ with a scanning step size of $0.2\ \mu\text{m}$, yielding $600 \times 600 = 360,000$ data points per area.

4. Results

4.1. Finite Element Simulation Results and Analysis

Figure 7 illustrates the distribution of creep damage at a certain moment during the creep process for joints with two different groove geometries. As observed, cracks form and propagate in the HAZ of the joint with a V-shaped groove, while in the joint with a stepped groove, cracks include both the upper and lower parts of the step. The two sets of cracks form and propagate in their respective HAZs and are separated by the horizontal step without merging. Looking at the crack propagation path in the joint with a stepped groove, the stepped shape can achieve the purpose of separating the upper and lower cracks. The upper crack tends to deflect into the base metal ahead of the interface (Region A), while the lower crack is constrained at the corner of the step (Region B). It is generally believed that the base material has better creep resistance than the HAZ, and crack propagation in the base material could potentially extend the creep life of the DMW.

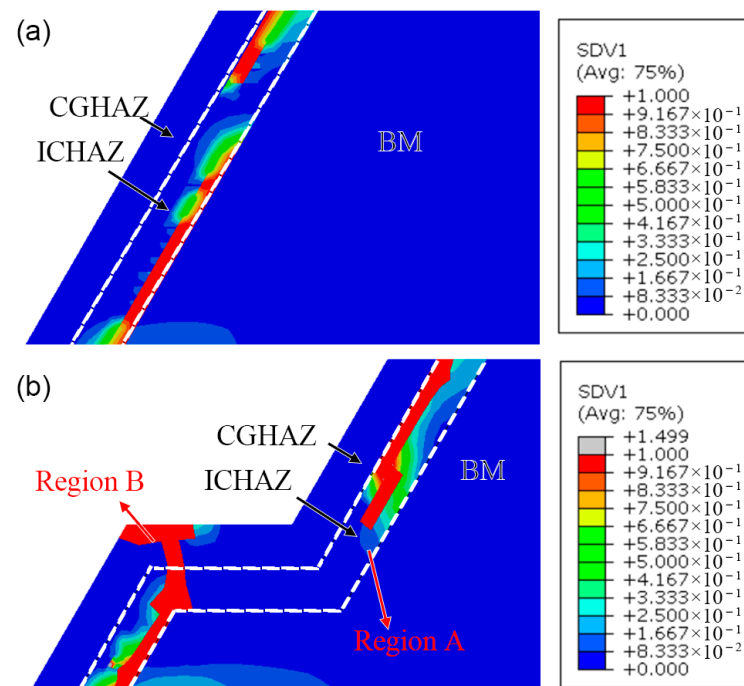


Figure 7. Simulation results of damage variables after crack propagation in joints with two types of groove geometries during the creep process, where (a) denotes the V-groove and (b) represents the stepped groove.

It can be anticipated that the joint with a V-groove will fracture rapidly after this time, while the joint with a stepped groove will have their crack propagation paths separated by the step. The upper crack will continue to propagate into base material, and the lower crack may enter weld metal, which could result in a longer creep life.

4.2. Creep Test Results and Analysis

Figure 8 shows the creep specimens after fracture, while Figure 9 presents the SEM images of the macroscopic morphology on both sides of the fractures for the V-groove and stepped groove joints. The deformation–time curve of the gauge section during the creep process is shown in Figure 10, which indicates that the V-groove weld joint has a shorter creep life (3309 h) and undergoes greater deformation (5.72%) compared to the stepped groove joint (life 3662 h, deformation 2.74%).

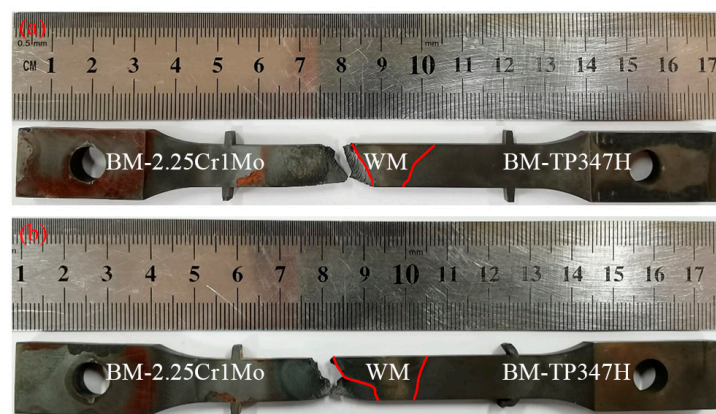


Figure 8. Macro photographs of the creep fracture specimens, where (a) is the V-groove weld joint; (b) is the stepped groove weld joint.

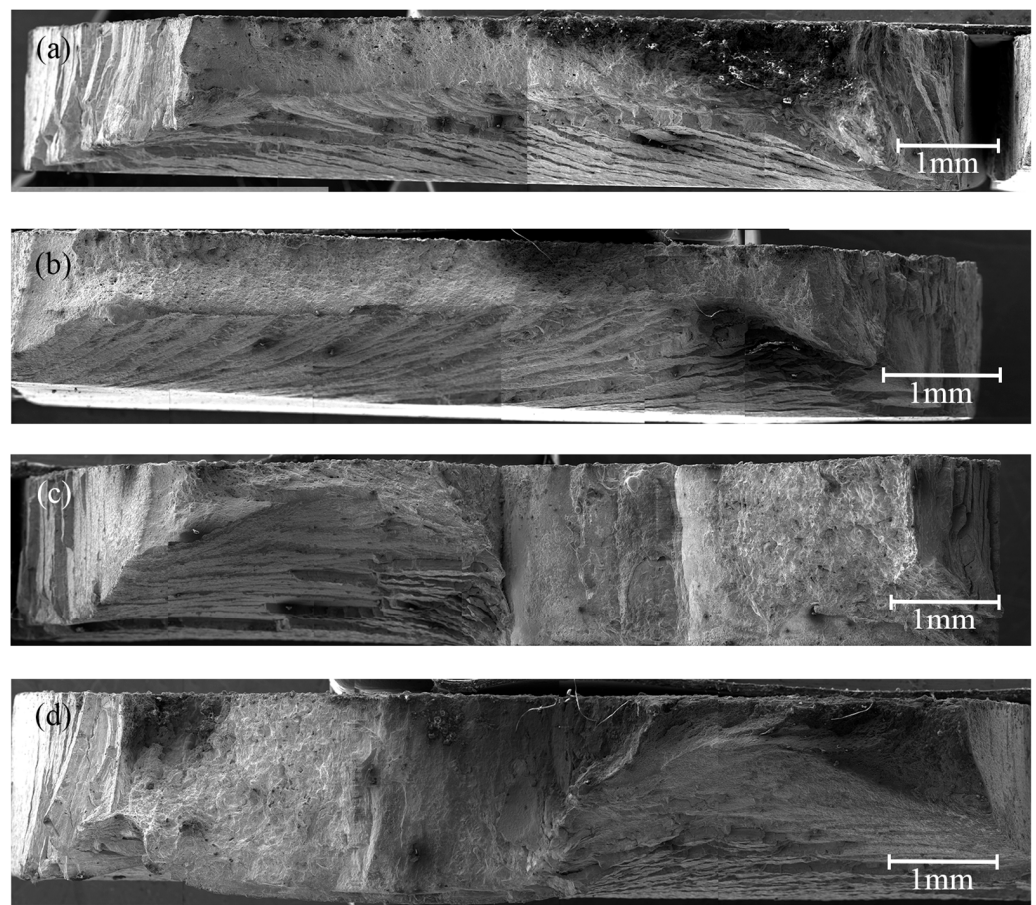


Figure 9. Macro SEM images of the creep fracture specimens, where (a) is the WM side of the V-groove weld joint; (b) is the BM-2.25Cr1Mo side of the V-Groove weld joint; (c) is the WM side of the stepped groove weld joint; and (d) is the BM-2.25Cr1Mo side of the stepped groove weld joint.

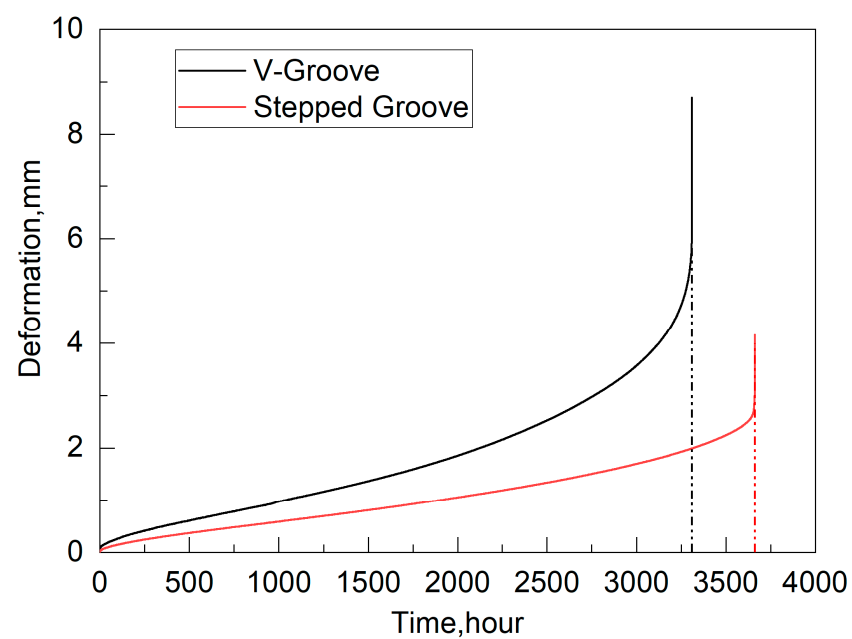


Figure 10. Deformation–time curves of the V-groove and stepped groove weld joints' gauge length during the creep test. (The dashed lines indicate the time at which failure occurred.)

4.3. Crack Propagation Path and Hardness Test Results

Figure 11 displays the micrographs of the cross-section near the fracture location on the 2.25Cr1Mo side, with blue lines indicating the hardness test paths. For the V-groove weld joint, the failure occurs within the HAZ of 2.25Cr1Mo steel, nearly parallel to the weld/2.25Cr1Mo interface. Conversely, in the stepped groove joint, the failure is located close to the weld/2.25Cr1Mo interface. The degree of plastic deformation of the specimen suggests that the crack initiates near the interface in the upper half. As it extends to the midpoint of the specimen—reaching the stepped “landing” of the joint—it no longer propagates along the interface but instead progresses into the base metal below until cracked, resulting in significant plastic deformation at the final cracking location.

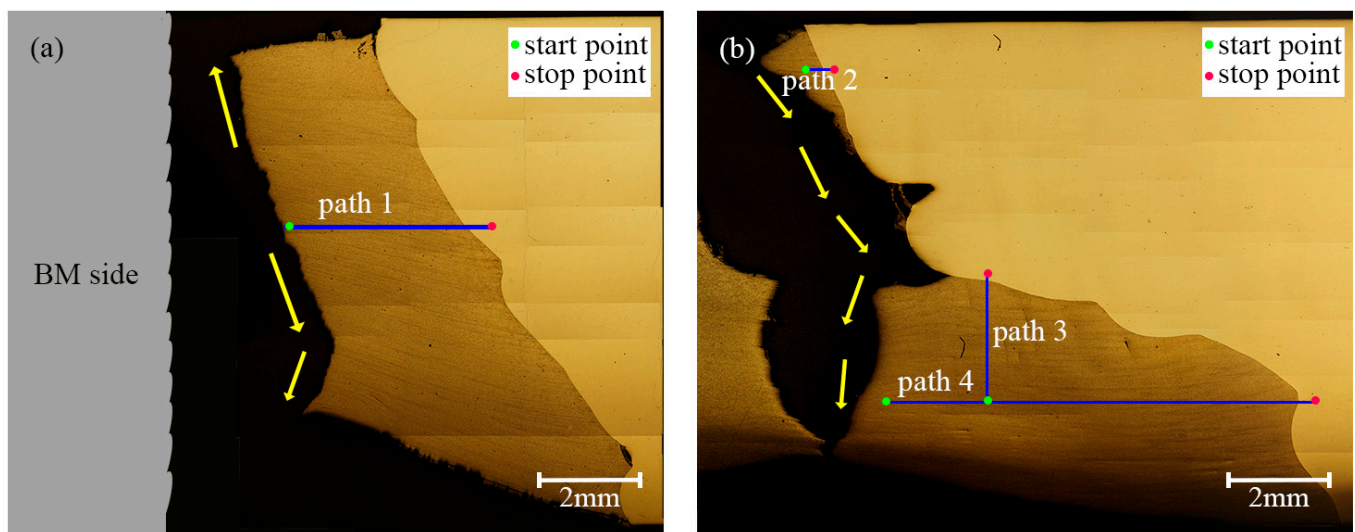


Figure 11. Optical micrograph of the creep fracture specimens for two different groove shapes, where (a) is the V-groove specimen; (b) is the stepped groove specimen. The red dashed line in the figure indicates the path of microhardness testing.

Figure 12 presents the hardness test results of the two specimens. For the V-groove specimen, the hardness does not change significantly from the fracture to the vicinity of the interface, with the weld hardness being significantly higher than that of the HAZ; for the stepped groove specimen, as shown in Figure 12b, the hardness distribution in the region above the fracture is essentially consistent with that of the V-groove joint, that is, the HAZ hardness is between 150 HV and 175 HV, and the weld hardness is around 250 HV.

Figure 12c shows the hardness distribution along Path 3 in the stepped groove specimen. It can be seen that the hardness decreases first and then increases from the fracture towards the weld direction. The hardness near the fracture is around 200 HV, and it decreases to 150 HV~175 HV in the area further away from the fracture. This hardness value is consistent with the HAZ hardness values measured in Figure 12a,b, indicating that the area with lower hardness values in Figure 12c is also part of the HAZ. The area closer to the crack with higher hardness is likely to be the base material. The hardness distribution shown in Figure 12d is consistent with that in Figure 12a,b, suggesting that there is a significant hardness gradient between the nickel-based weld and the HAZ. This mechanical property difference can impose structural constraints on the material near the interface during the creep process, thereby affecting the development of creep damage.

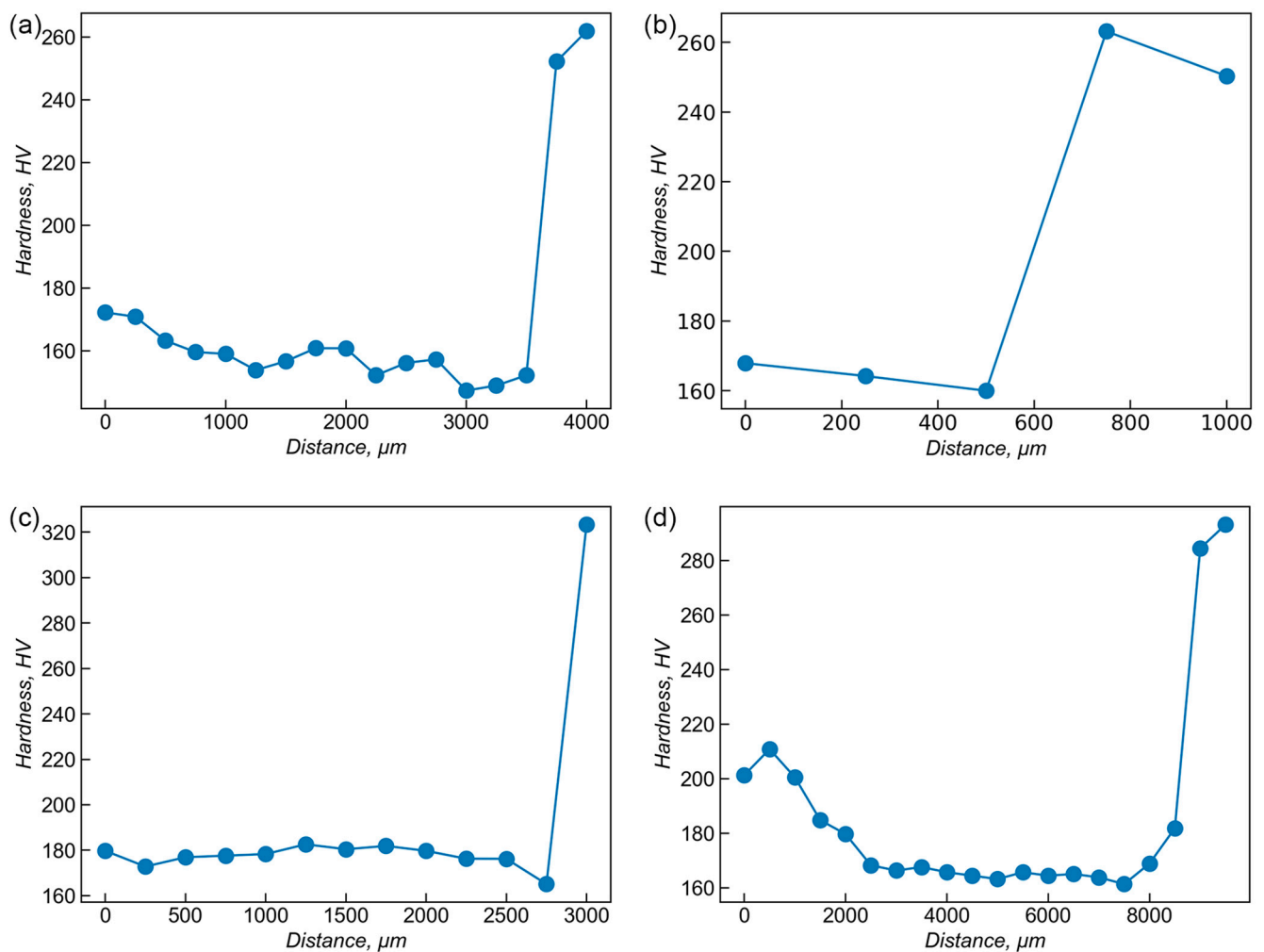


Figure 12. Hardness distribution at different locations after creep fracture of joints with two types of groove geometries: (a) Path 1; (b) Path 2; (c) Path 3; (d) Path 4.

4.4. Microstructural Observation

For the V-groove specimen, the fractured specimen was observed using an optical microscope, as shown in Figure 13. The areas near the crack propagation path, as marked in Figure 13, were examined by SEM, revealing no signs of creep damage at location 1, where a distinct oxidation layer and elongated grains resulting from plastic deformation were observed. At location 2, located in the middle of the crack, an oxidation layer and evident creep voids were also observed near the fracture surface, suggesting that this area might be where creep voids coalesce into microcracks and slowly develop into macroscopic cracks. At location 3, below the corner, neither a distinct oxidation layer nor creep voids were seen in the cross-section. Additionally, the grains appeared significantly elongated, indicating that substantial plastic deformation had occurred at this location and that the crack propagation was too rapid to form an oxidation layer.

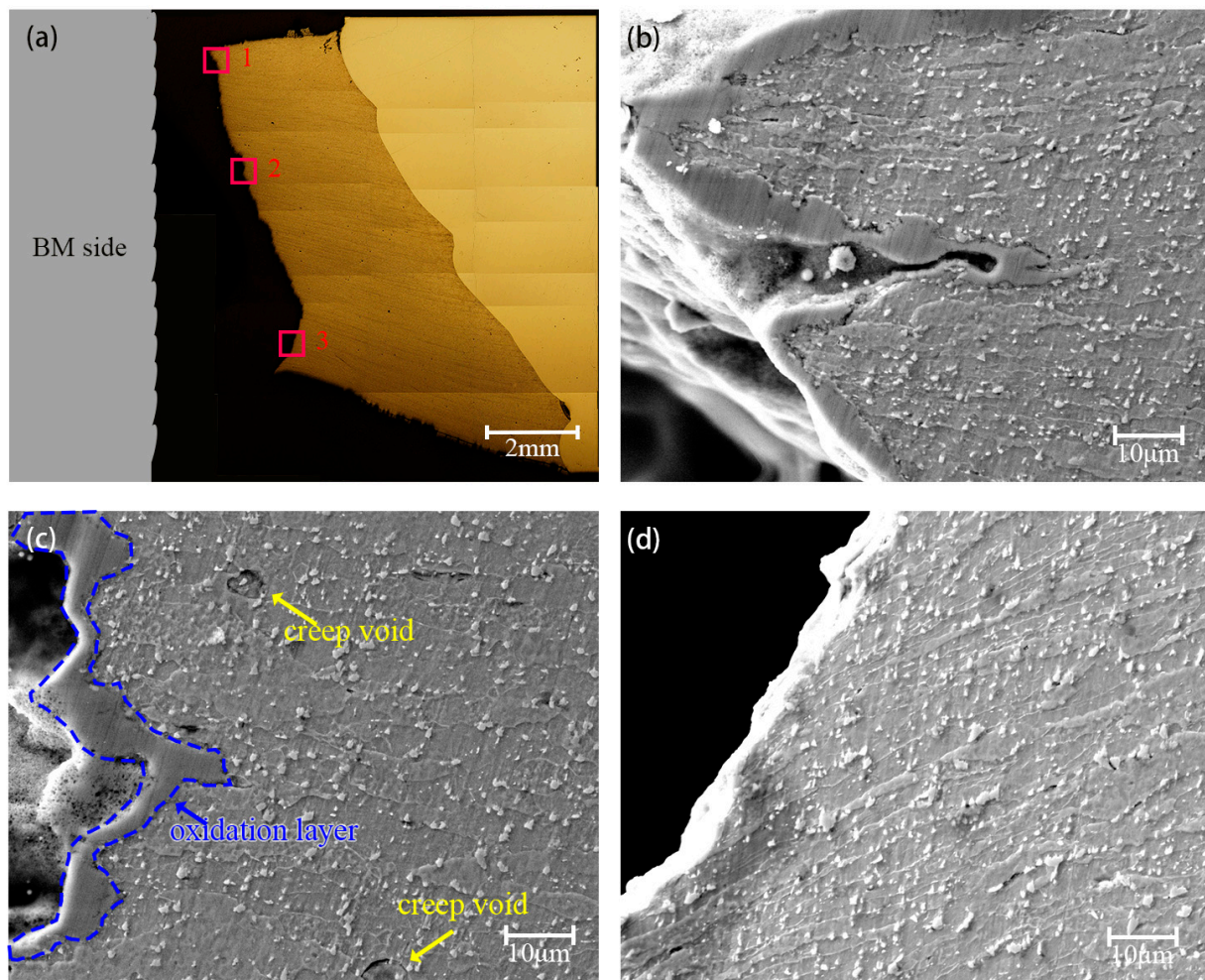


Figure 13. Microstructural image of the V-groove specimen after fracture, where (a) is the macroscopic metallography, and (b–d) are SEM magnified images of areas 1 to 3 in figure (a).

As previously mentioned, the creep crack in the stepped groove joint formed in the HAZ of 2.25Cr1Mo and propagated along the interface between the weld and the HAZ, eventually entering the 2.25Cr1Mo base metal. As shown in Figure 14a, SEM observations at different locations of the fractured specimen revealed that the weld/heat-affected zone interface near the crack was well bonded, with no apparent signs of creep damage, as shown in Figure 14b. At the step of the groove, the crack was observed to stop propagating after extending a certain distance, as shown in Figure 14c. A layer of oxidation about 10 µm thick, outlined by the blue dashed line, was visible at the crack tip, suggesting that oxidation at the crack tip might also contribute to the development of creep cracks. Creep voids, indicated by the yellow arrows, were observed at the crack tip, located approximately 10 µm from the weld/HAZ interface, indicating that the creep crack did not strictly propagate along the interface but rather through the HAZ very close to the interface. As the crack continued to propagate downward into the base metal, the number of creep voids, marked by yellow arrows, in the nearby area of the crack propagation path decreased, as shown in Figure 14d,e, which might be related to the imminent transition to rapid fracture. Additionally, some large creep voids, highlighted by yellow arrows, were observed in the area at the bottom of the joint near the interface (area 5 in Figure 14a), as shown in Figure 14f, but they did not coalesce into cracks.

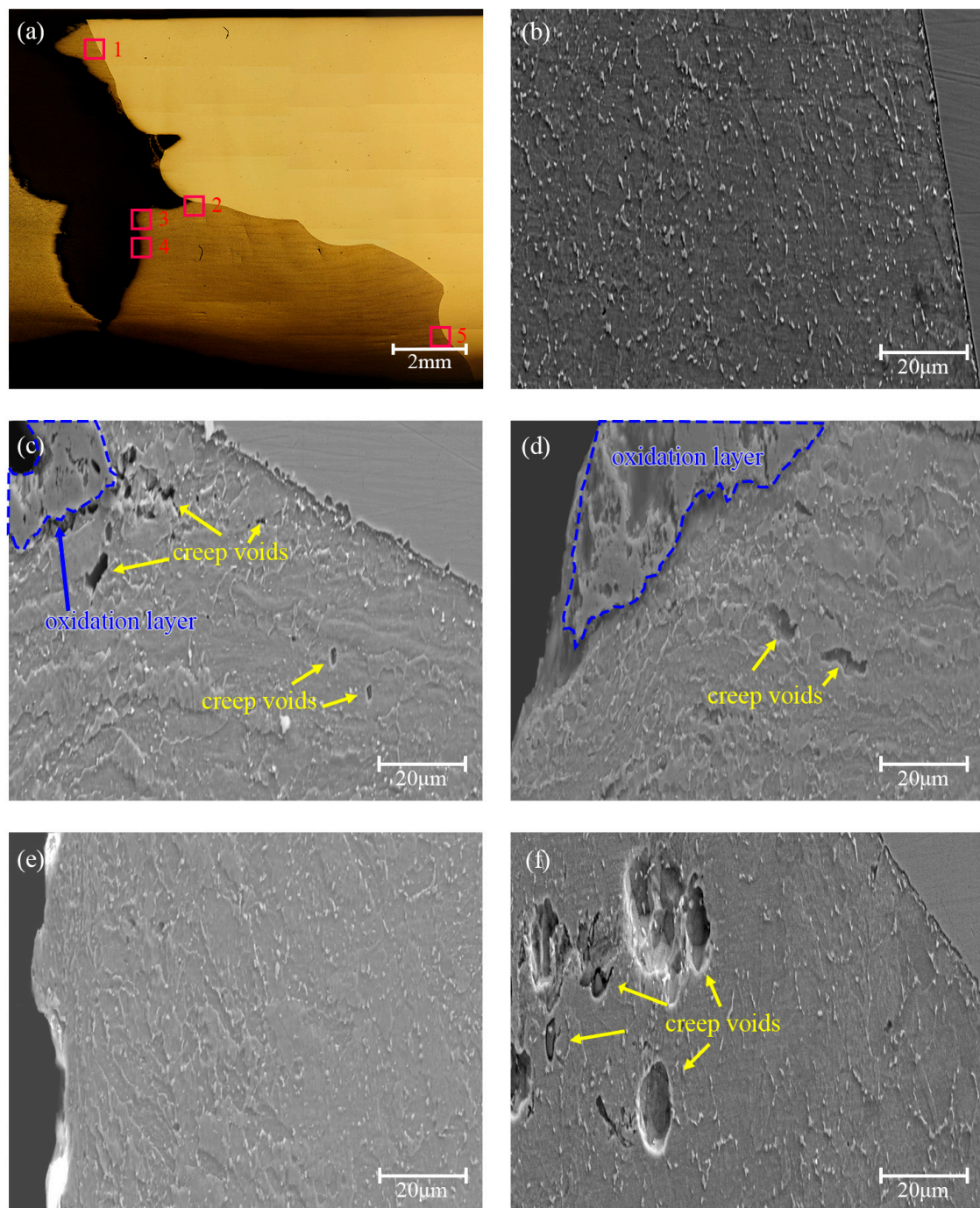


Figure 14. Morphology at different positions along the crack propagation path of the creep specimen after fracture of the stepped groove joint, where (a) is the macroscopic metallography, and (b–f) are SEM magnified images of areas 1 to 5 in Figure (a).

4.5. EBSD Results

An EBSD analysis was conducted on some locations of the two failed joints. Figure 15 shows three areas near the fracture of the V-groove specimen that were analyzed, with Area 2 and Area 3 close to the crack edge. Area 2 is near the crack initiation site, Area 3 is near the rapid fracture zone, and Area 1 is about 1mm away from the fracture. The analysis results of the three areas are shown in Figure 16.

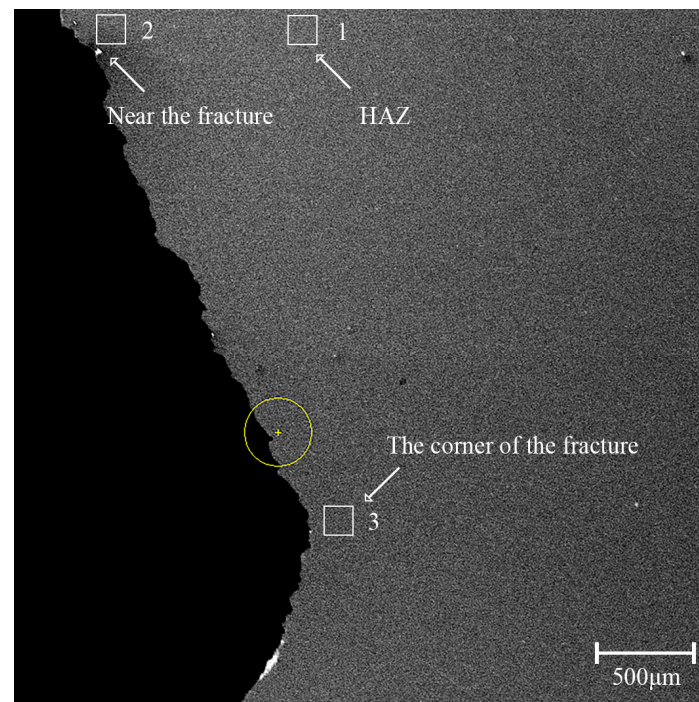


Figure 15. Selected EBSD scanning area of V-groove specimen.

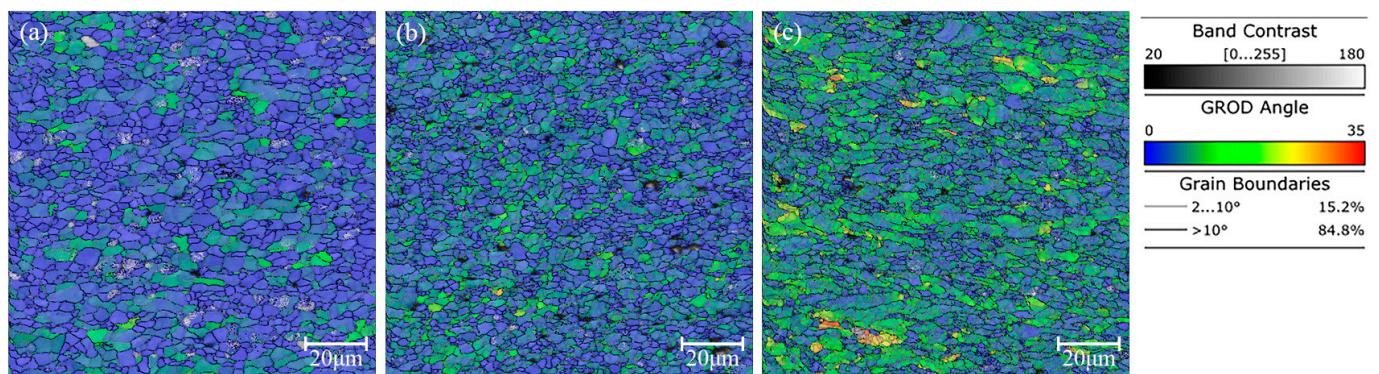


Figure 16. GROD distribution in the areas near the fracture of the V-groove joint specimen: (a–c) correspond to the GROD distribution in Areas 1–3 of Figure 15, respectively.

Figure 16 shows the GROD results for the three areas of the V-groove joint. In terms of grain morphology, the grains in Area 3 are significantly elongated, indicating that significant plastic deformation has occurred in this area, which is consistent with the previous analysis. The GROD value in this area is significantly higher than the values in Areas 1 and 2, which also indicates that the sum of the plastic strain produced during the rapid fracture process and the previously accumulated creep strain is the greatest in this area. Compared to Area 1, Area 2 has a smaller grain size, suggesting that it is likely to be the critical heat-affected zone or the fine-grained zone within the heat-affected area, and its GROD value is somewhat higher. Considering that no significant plastic deformation has occurred in these two areas, the difference in GROD values is mainly due to the variation in creep deformation, indicating that the creep damage in Area 2, which is closer to the fracture, is greater than that in Area 1, which is further away from the fracture.

Figure 17 displays three areas near the fracture of the stepped groove specimen selected for analysis. Areas 1 and 2 are situated in the base metal below the step, near the central position on the crack propagation path, and closer to the crack propagation path. Area 3 is

near the end of the crack propagation path and is further away from the crack compared to Areas 1 and 2. The analysis results of these three areas are presented in Figure 18.

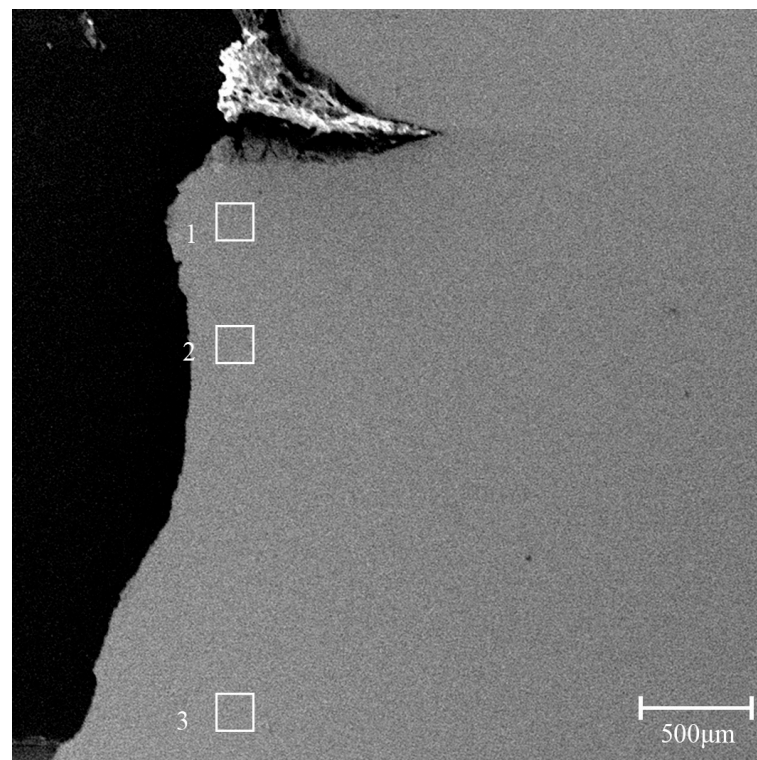


Figure 17. Selected EBSD scanning area of stepped groove specimen.

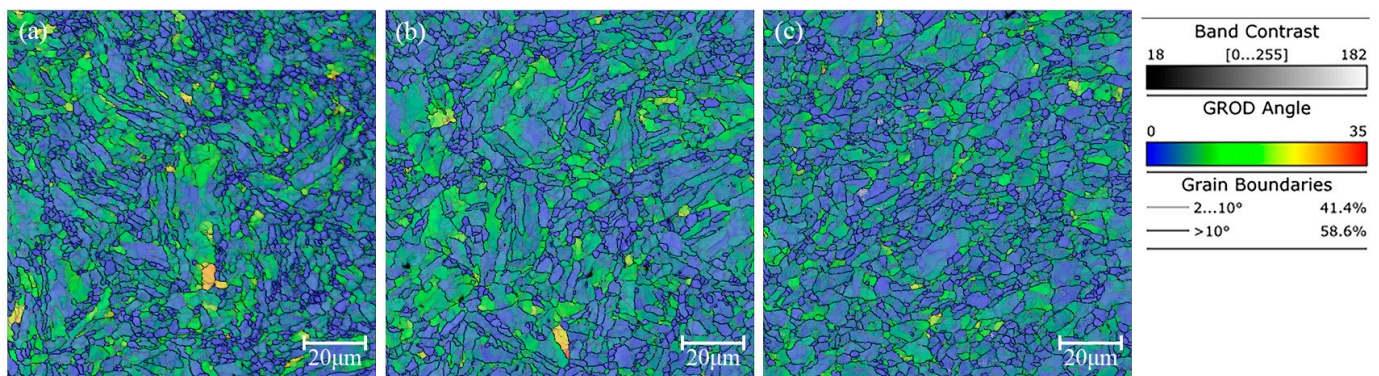


Figure 18. GROD distribution in the areas near the fracture of the stepped groove joint specimen: (a–c) correspond to the GROD distribution in Areas 1–3 of Figure 17, respectively.

The GROD values were statistically analyzed to obtain the average GROD ($\overline{GROD}$) for each micro-area, with the calculation formula as follows:

$$\overline{GROD} = \frac{1}{360000} \sum_{m=1}^{600} \sum_{n=1}^{600} GROD(m, n) \quad (5)$$

The obtained $\overline{GROD}$ values for each analysis location of the two specimens are listed in Table 5. It can be seen from the table that the degree of creep deformation near the failure location of the stepped groove joint is significantly higher than that of the V-groove joint, indicating that the creep damage near the fracture location of the stepped groove joint is greater, and the reason for this will be discussed in the following section.

Table 5. $\overline{GROD}$ of different regions in the two failed joints.

	Location 1	Location 2	Location 3
V-groove test specimen	2.1013	3.1789	5.6717
Stepped groove test specimen	5.2947	5.1296	4.6076

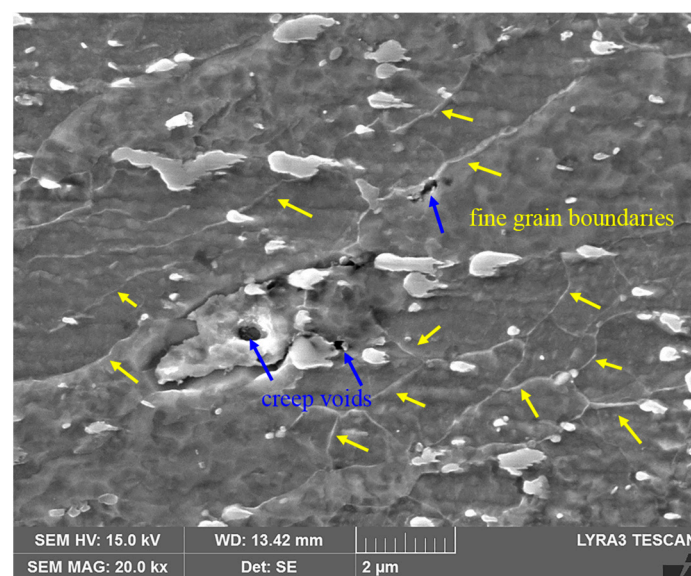
5. Discussion

In this section, we focus on the analysis of both the simulation and experimental results to discuss the failure mechanisms of two joints, as well as the influence of the stepped groove on the creep fracture behavior.

5.1. Analysis of Joint Failure Mechanisms

5.1.1. Failure Analysis of V-Groove Joints

Based on the results of hardness tests and fracture location analysis, it is evident that the creep failure of the V-groove joints was mainly located in the region with the lowest hardness within the HAZ. The EBSD analysis results showed that the grain size near the failure location was significantly smaller than that of the grains farther away from the failure location. Based on both hardness and grain size, it can be determined that the failure location of the V-groove joint is either in the fine-grained zone or in the inter-critical zone of the HAZ. For ferritic heat-resistant steel welded joints, the creep fracture mode occurring in these two areas is referred to as Type IV fracture [37]. Generally, this type of failure mode is mainly related to the lack of precipitate pinning at grain boundaries, coarsening of precipitates, and structural constraints due to lower hardness [38,39]. Vanaja et al. [13] also reported Type IV failure in the inter-critical HAZ of Grade 91 steel in an electron-beam-welded DMW after long-term creep exposure. Kumar et al. [9] identified the fine-grained HAZ as the weakest region in terms of creep strength in a laser-beam-welded IN617/304L DMW joint. Similar phenomena were also observed in the area near the crack of the failed specimen, as shown in Figure 19. The grains in the area shown in the figure are smaller than 10 μm , and there is a lack of precipitates on the grain boundaries (indicated by yellow arrows). Some large carbide particles can be observed in the matrix, and creep voids (marked by blue arrows) can be seen around these carbide particles or at the grain boundaries. These phenomena indicate that the creep fracture failure of the V-groove joint is indeed dominated by the Type IV fracture mode.

**Figure 19.** SEM image of the area near the crack in the V-groove joint.

5.1.2. Mechanical Factors Contributing to Creep Failure

Additionally, the mechanical property differences reflected by the hardness distribution are also an important factor promoting creep fracture failure in this region. Albert [7] pointed out that under uniaxial high-temperature creep conditions, the FGHAZ is subjected to a triaxial tensile stress state, and the triaxiality of stress in this region is significantly higher than that in other areas, which is the mechanical factor leading to the formation of creep voids and subsequently Type IV fracture. As can be seen from the hardness test results in Figure 12, both the base material and the weld have higher hardness compared to the HAZ in the middle position. This led to restraint by the surrounding material during uniaxial creep, resulting in higher stress triaxiality in the FGHAZ/ICHAZ, which promotes the formation of creep voids. Unlike the V-groove joints, the fracture location of the stepped groove joints was closer to the weld/HAZ interface, and only when the crack extended to the platform position of the step did it enter and propagate in the 2.25Cr1Mo base material. Since the welding and heat treatment processes for both types of joints were consistent, the influence of microstructure on the fracture mode can be ruled out, leaving the most likely influencing factor to be the change in stress distribution due to the alteration in the groove geometry. To verify this hypothesis, equivalent stress distribution maps near the weld/HAZ interface at the initial stage of creep for both types of joints are presented in Figure 20. It can clearly be seen that the equivalent stress level gradient on both sides of the interface for the stepped groove joint is significantly higher than that of the V-groove joint, which may be an important factor leading to the shift of the fracture location from the middle of the HAZ to the interface. This stress concentration effect of the stepped groove was also observed by Santoso et al. [15] in their study on T91/347H DMWs. Bhanu et al. [10,11] reported that the residual stresses in P91/Incoloy 800HT DMWs were significantly affected by the groove geometry and post-weld heat treatment process.

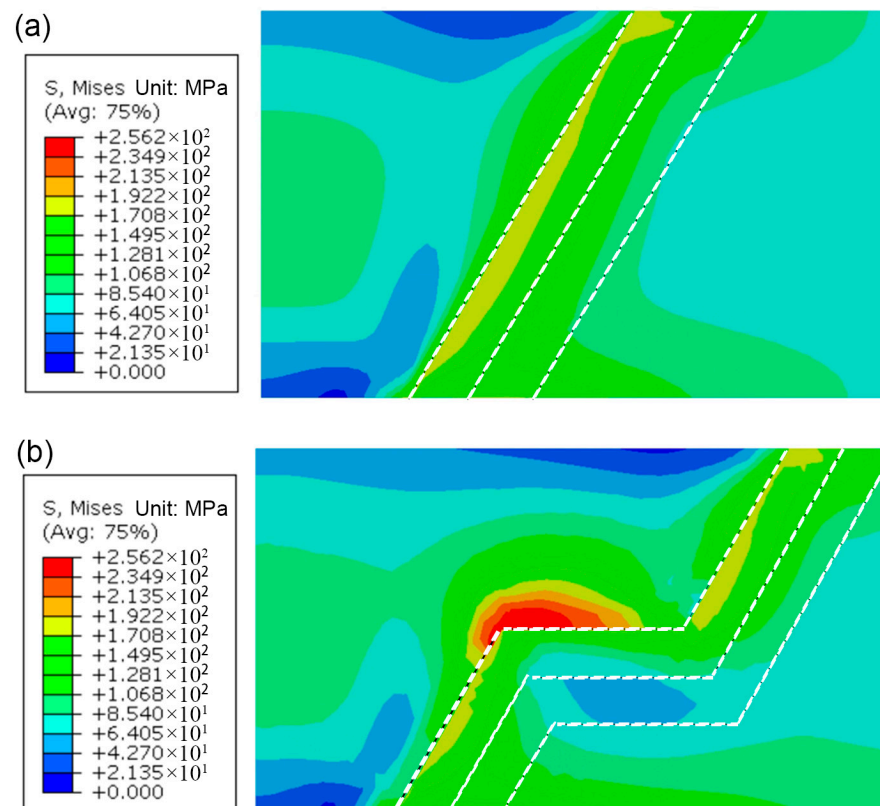


Figure 20. Distribution of Mises equivalent stress near the interface at the initial stage of creep for two types of groove-shaped joints, where (a) is the V-groove joint and (b) is the stepped groove joint.

In addition to the experimental observations, the simulation results also demonstrated the effectiveness of the improved creep damage model in capturing the creep damage behavior in DMWs. As shown in Figure 20, the improved model predicted the stress concentration near the interface, which is consistent with the phenomena observed in actual DMWs. Although this is a qualitative conclusion rather than a quantitative one, improvements will be made in our future work.

5.2. The Role of the Stepped Groove

5.2.1. Impact of the Stepped Groove on Crack Propagation

The results of the simulation showed that in the stepped groove joint, after the creep crack extended to the “step” position, it did not continue to propagate along the horizontal interface at the “step”. From the perspective of stress triaxiality and creep damage distribution, the crack was more inclined to propagate into the base metal or weld metal ahead of the crack tip. The reason for this phenomenon is that, on the one hand, the interface at the “step” is parallel to the direction of the external load, and if the crack turns to propagate along the interface, it would change from a Mode I to a Mode II crack, and the latter requires a greater driving force for propagation, which is clearly not conducive to crack development. On the other hand, the creep resistance of the base material and weld metal is stronger than that of the HAZ, so when the crack extends to these two areas, the rate of propagation decreases due to the slower development of creep damage. This might be the reason why the creep life of the stepped groove joint was longer compared to the V-groove joint. In addition, the EBSD analysis results of the fractured specimens showed that when the creep crack developed into the base metal in the lower half of the stepped groove joint, the required creep strain (average Grain Reference Orientation Deviation, ($\overline{GROD}$)) was larger compared to the HAZ (see Table 5), which again proves that the superior creep resistance of the base material leads to a slower crack propagation in the base material. Similar crack deflection and retardation effects of the stepped groove were reported by Parker et al. [17] in their creep tests of P91 steel welds.

5.2.2. Creep Life Extension and Deformation Monitoring

The results of the creep tests also proved that the stepped groove is more beneficial for extending the creep life of the joint. Looking at the crack propagation path, the stepped groove had indeed played a role in altering the crack propagation path, confirming the results of the simulation calculations. However, from the deformation results of the gauge length area measured in the creep tests (Figure 8), the creep deformation of the stepped groove joint was less than that of the V-groove throughout the creep process, which was disadvantageous for high-temperature service online monitoring of the joint, as smaller deformations are less likely to be detected in the field. Moreover, from the $\overline{GROD}$ results (Table 5), the creep deformation near the crack in the stepped groove joint was significantly greater than that in the V-groove joint. But considering that the deformation of the entire gauge length for the former is less than that of the latter, it can be concluded that the deformation during the creep process was more concentrated in the stepped groove joint, which might accelerate the development of creep damage.

5.2.3. Simulation and Stress Concentration Effects

In addition, simulation results (Figure 20) showed that the stepped groove intensified the equivalent stress concentration near the weld/HAZ interface at the initial stage of creep, which could accelerate interfacial damage. This negative effect partially offsets the benefit of altering crack paths. Therefore, the geometry of the stepped groove needs to be carefully designed. Ragab et al. [27] emphasized the importance of incorporating the multi-axial stress state and ductility exhaustion in modeling the creep damage behavior of Grade 91 steel welds. They also pointed out the need for developing improved creep-ductility-based constitutive models to enable a more accurate life assessment [28]. To mitigate the interfacial stress concentration while preserving the crack deflection capability, reducing

the height of the step may be beneficial. This will be a focus of our future research to optimize the stepped groove configuration for DMWs.

In summary, the stepped groove extends the creep life of the joint by altering the crack propagation path, while it also accelerates the concentration of stress near the interface due to the changed groove geometry, thereby accelerating the development of creep damage. Therefore, the impact of the stepped groove on the creep life of the joint is a balanced result of these two effects. To optimize the design of DMWs with complex geometries for enhanced creep life, a good balance must be achieved between the negative effect of the interfacial stress concentration and the positive effect of crack path deflection induced by the stepped groove.

6. Conclusions

This study conducted finite element simulation and experiments to investigate the impact of groove geometry on the high-temperature creep life of DMWs. The creep life, failure location, and failure mechanism of these two joints using V-shaped and stepped grooves were discussed, and the following conclusions were reached:

1. An improved creep damage model considering stress triaxiality was proposed to simulate the damage evolution in the structurally constrained regions near dissimilar interfaces. Compared with the conventional L-M model, the new model can better capture creep damage localization in complex DMW structures.
2. The simulation results indicated that the stepped groove could alter the creep crack propagation path, preventing it from extending along the weld/HAZ interface at the “step” and instead propagating into the base metal or weld with better creep properties. This delayed the development of creep cracks and served to prolong the life of the joint.
3. The failure location of the DMW with a V-groove was in the HAZ, characterized by a typical Type IV fracture, mainly related to factors such as lower hardness in the fine-grained zone/critical HAZ, lack of carbide pinning at grain boundaries, and coarsening of carbides. The creep failure of the DMW with a stepped groove initially occurred along the weld/HAZ interface, which might be associated with a higher interfacial stress gradient. When the crack propagated along the interface to the “step,” it then entered into the base metal.
4. The impact of the stepped groove on the creep life of DMWs was the balanced result of two contradictory factors: on the one hand, it extended the creep life by changing the crack propagation path, and on the other hand, it exacerbated the stress concentration at the interface, accelerating the development of interfacial creep damage. Proper design of the step geometry is needed to maximize the positive effect while minimizing the negative effect.

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