Vol. 51 No. 4

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2023-03-19

ChinaRxiv

Abstract

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Full Text

Vol. 51 No. 4
Apr. 2015 pp. 393–399

Carbon Diffusion in Cr5Mo/A302 Dissimilar Welded Joints and Its Effect on High-Temperature Creep Life*

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Abstract Based on aging-treatment experiments, microhardness measurements, and Fick' s second law, the carbon diffusion behavior of Cr5Mo/A302 dissimilar welded joints was investigated. Subsequently, creep tests were carried out on dissimilar welded joints containing a pre-existing 200 μm decarburized layer and on as-welded joints without a decarburized layer, in order to study the influence of the decarburized layer on joint life under different stress levels. The results show that, with increasing aging time, carburization and decarburization become more severe, and the width variations of both the carburized and decarburized layers follow a parabolic law. The experimental measurements are basically consistent with the fitting results obtained from Fick' s second law.

Under high-stress conditions, the pre-formed decarburized layer can reduce the long-term high-temperature life of the joint by several times and cause premature cracking of the joint. However, as the stress level decreases, the cracking time continuously increases and the influence of the pre-formed carbon diffusion on the long-term life of the joint continuously declines. When the stress is reduced to below 36% of the tensile strength of the joint, its influence can be neglected. A relationship between the carbon-diffusion influence factor S and stress was established, and the critical stress value below which the existing decarburized layer has no effect on high-temperature long-term life was determined.

Key words Cr5Mo/A302 dissimilar welded joint; carbon diffusion; carbon-diffusion influence factor S

Chinese Library Classification No. TG457.11, TG113.3 **Document code** A **Article No.** 0412-1961(2015)04-0393-07

CARBON DIFFUSION AND ITS EFFECT ON HIGH TEMPERATURE CREEP LIFE OF Cr5Mo/A302 DISSIMILAR WELDED JOINT

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Supported by National Natural Science Foundation of China (No.10172046)

Manuscript received 2014-08-04, in revised form 2014-12-10

ABSTRACT Based on the consideration of economy and being easy to construct on site, Cr5Mo/A302 dissimilar welded joints are widely used in elevated temperature applications such as coal-fired power station, nuclear plant and petrochemical industry. Because of the difference in carbide forming elements on both sides of welded joint fusion line, carbon diffusion will happen in service progress and induce premature invalidation. The calculation methods of carbon diffusion and its harm to creep life of dissimilar welded joints have been investigated in the past decades. Theoretically, at a certain temperature, creep damage mechanism changes according to stress levels. However, the previous works paid little attention on the effect of carbon diffusion to creep life at different stress levels and few studies have been done focusing on relationships among carbon diffusion degree, stress level and creep life. In this work, carbon diffusion behavior of Cr5Mo/A302 dissimilar welded joint was first studied by employing aging treatment test, micro-hardness measurement and Fick's second law. Subsequently, creep tests were performed to investigate the effect of 200

μm wide decarburized zone on the joint creep life at different stress levels. The results showed that carbon diffusion in Cr5Mo/A302 dissimilar welded joints became serious with the in-

* Supported by National Natural Science Foundation of China, Grant No. 10172046

Received: 2014-08-04; revised: 2014-12-10

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DOI: 10.11900/0412.1961.2014.00435

crease of aging treatment time. The widths of the carbon-rich zone and decarburized zone were both consistent with the parabolic distribution law and could be simulated by Fick' s second law. The decarburised zone, which formed in the process of aging, reduced the creep life of the joint greatly at high stress levels. However, with the decline of testing load, its effect became much smaller. When the stress level dropped to about 36% of the yield stress, its effect was negligible. Meanwhile, the relationship of stress and carbon diffusion impact factor S was established to determine the critical value of the stress below which the decarburised zone would not affect the high-temperature creep life of the dissimilar joint.

KEY WORDS Cr5Mo/A302 dissimilar welded joint, carbon diffusion, carbon diffusion impact factor S

Cr–Mo heat-resistant steels possess good creep strength, oxidation resistance, and economy, and are widely used in the manufacture of high-temperature equipment in industries such as thermal power, nuclear power, and petrochemicals. For reasons of economy and ease of construction, welding of Cr–Mo heat-resistant steels often uses austenitic stainless-steel welding consumables, such as A302 welding rod. This welding process requires neither preheating before welding nor postweld heat treatment after welding, which not only reduces energy consumption and cost, but also facilitates on-site installation of large equipment. However, in actual high-temperature service, C will diffuse from the side with a low alloy-element content (generally the base metal) toward the side with a high alloy-element content (generally the weld), affecting the service performance of the joint. Studies [1–8] have shown that C diffusion leads to a reduction in high-temperature creep rupture life and causes early failure; the creep cracking position is mainly concentrated in the decarburized layer. C diffusion in dissimilar welded joints is a multicomponent-system diffusion process, and its driving force is the chemical-potential gradient of C on the two sides of the fusion interface. Driven by the chemical-potential gradient, C diffuses from the side with higher activity to the side with lower activity. The effective activity of C is affected comprehensively by alloying elements such as C, Cr, Ni, Mn, Mo, and Ti [9–12]. In dissimilar welded joints, because the diffusivity of C in α-Fe is much greater than that in γ-Fe (39 times greater at 910 °C, 126 times greater at 755 °C, and 835 times greater at 500 °C [13]), it is difficult for C to undergo long-range diffusion into the austenitic weld. Therefore, C is mainly distributed in the martensite (M) region or martensite-like (M-L) region of the weld close to the fusion line [14–16], and follows the parabolic law [4,17]. Researchers [12,18,19] used the error-function solution of Fick' s law to calculate and analyze C diffusion behavior, and the results were basically consistent with experiments. Shi Chunyuan et al. [20] and Yang Houjun et al. [21] used nonlinear regression and finite-difference methods, respectively, to calculate and analyze C diffusion behavior, and the trends were also consistent with experimental results. However, there have been no reports on comparisons between the life of joints after a certain degree of C diffusion has occurred and that of newly welded joints, or on the relationship between differences in life and stress level.

In this work, based on aging experiments and in conjunction with Fick' s second law, the C diffusion behavior on both sides of the fusion line in Cr5Mo/A302 dissimilar welded joints was studied. Based on creep rupture tests, the effect of stress level on the high-temperature life of welded joints was investigated after an approximately 200 μm decarburized layer already existed in the dissimilar welded joint.

1 Experimental Methods

The base metal of the welded joint used in the experiment was a Cr5Mo steel pipe with a diameter of 198 mm, wall thickness of 12 mm, and length of 600 mm. A 60° V-groove was used; SH S820 welding wire was used for argon-arc welding backing, and A302 austenitic welding rod was used for argon-arc welding filling. The weld was completed in four passes. The interpass temperature was controlled below 150 °C, and no preheating or postweld heat treatment was carried out during welding. The chemical composition (mass fraction, %) of the Cr5Mo base metal was: C 0.14, Si 0.27, Mn 0.38, S 0.005, P 0.018, Cr 5.9, Mo 0.5, Fe balance. The chemical composition (mass fraction, %) of the A302 welding rod was: C 0.08, Si 0.47, Mn 1.62, S 0.015, P 0.032, Cr 22, Ni 12.9, Mo 0.15, Fe balance.

Aging experiments were carried out in an SX-2.5-1 box-type resistance furnace temperature-controlled by an AI-708 industrial regulator. The aging temperature was 650 °C, and the aging times were 100, 257, 460, and 1160 h. The hardness distribution near the fusion zone of the welded joint was measured with an HXD-1000TM hardness tester. The C content near the fusion line of the welded joint was analyzed using an EPMA-1610 electron probe microanalyzer (EPMA).

High-temperature tensile and rupture specimens with welds were machined from the as-welded and 650 °C, 257 h aged Cr5Mo/A302 welded joints (at which time a decarburized layer about 200 μm wide appeared in the joint), with the weld located in the middle of the specimen. High-temperature tensile tests at 550 °C were carried out on an EHF-EG250-40L material testing machine, and constant-load creep rupture tests at 550 °C and 80–180 MPa were carried out on an RD2-3 creep rupture testing machine. An XJZ-6 optical microscope (OM) was used for microscopic observation of the C diffusion characteristics of the welded joint and the fracture characteristics of the creep rupture specimens.

2 Experimental Results

2.1 Aging Experiment

OM images near the fusion line of Cr5Mo/A302 dissimilar welded joints before and after aging are shown in Fig. 1. As can be seen from the figure, under the as-welded condition, no obvious C diffusion was observed in the Cr5Mo/A302 dissimilar welded joint. During aging at 650 °C, with increasing time, the carburized layer became increasingly wide and exhibited a serrated diffusion feature.

2.2 Hardness Test

The hardness distribution near the fusion line of the as-welded Cr5Mo/A302 dissimilar welded joint is shown in Fig. 2. It can be seen from the figure that, after welding, the overall hardness of the heat-affected zone of the Cr5Mo base metal increased, and a hardened layer about 3000 μm wide appeared. Metallographic observation showed that this region was the entire heat-affected zone of the base metal, including the coarse-grained zone, fine-grained zone, and part of the phase-transformation zone; the hardness exceeded

Figure 1 OM images of carbon-rich zones in Cr5Mo/A302 dissimilar welded joints in the as-welded state (a) and after aging at 650 °C for 100 h (b), 257 h (c), 460 h (d), and 1160 h (e)

Figure 2 Hardness distribution near the fusion line of the as-welded Cr5Mo/A302 dissimilar welded joint

380 HV, indicating that Cr5Mo has a relatively strong quench-hardening tendency; however, this hardened layer disappears after aging. Metallographic observations of the fusion zone (Fig. 1a) show that no obvious C diffusion occurred in the Cr5Mo/A302 joint during welding.

After aging at 650 °C for 100–1160 h, the hardness distribution near the fusion zone of the Cr5Mo/A302 dissimilar welded joint is shown in Fig. 3. It can be seen from the figure that, after aging, a decarburized layer appears in the heat-affected zone on the Cr5Mo base-metal side of the welded joint, and the hardness gradually decreases to about 230 HV, with the width gradually increasing to approximately 500 μm. A corresponding carburized layer appears on the weld side; although its width is very narrow, with a maximum of about 10 μm, the hardness increases to 350 HV.

2.3 High-temperature tensile and endurance tests

In high-temperature tensile tests on the Cr5Mo/A302 dissimilar welded joint, the fracture locations of the specimens were all in the base metal. For specimens without aging treatment,

The tensile strength of the welded joint in the as-welded state was $\sigma_b = 383$ MPa, the yield strength was $\sigma_{0.2} = 211$ MPa, and the elongation after fracture was $\delta = 22.5\%$. After aging at 650 °C for 257 h, the tensile strength of the welded joint was $\sigma_b = 358$ MPa, the yield strength was $\sigma_{0.2} = 200$ MPa, and the elongation after fracture was $\delta = 25.4\%$. The experimental results show that, after aging treatment, the strength of the Cr5Mo/A302 dissimilar welded joint decreased slightly, whereas the plasticity increased slightly.

Figure 4 compares the creep rupture lives of Cr5Mo/A302 dissimilar welded joints in the as-welded state and after aging at 650 °C for 257 h under different stress levels at 550 °C. It can be seen from the figure that the constant-load creep rupture lives of the as-welded dissimilar welded joint and the aged dissimilar welded joint at 550 °C under stresses of 180, 150, 130, 100, and 80 MPa were 113, 331, 511, 1293, and 2792 h, and 22, 117, 233, 933, and 2445 h, respectively. Except at the stress level of 180 MPa, where the fracture positions of the Cr5Mo/A302 dissimilar welded joint specimens in the two states were outside the base metal, the remaining specimens all fractured in the heat-affected zone of the base metal close to the fusion line. The creep rupture life data indicate that, at high stress levels, the life of the as-welded Cr5Mo/A302 dissimilar welded joint was significantly longer than that of the welded joint after aging treatment. For example, at 180 MPa, the creep rupture life of the as-welded Cr5Mo/A302 dissimilar welded joint was 5.14 times that of the aged joint. As the stress level decreased, the difference in life between the two gradually narrowed; when the stress decreased to 80 MPa, the difference in life between the two was only 12.4%.

The OM images of the fracture positions of Cr5Mo/A302 dissimilar welded joints in the as-welded state and after aging treatment under the test conditions of 550 °C and 100 MPa are shown in Fig. 5. It can be seen from the figure that the fracture positions were all located in the decarburized layer, but the fracture morphologies differed. The main crack in the as-welded joint was straight, whereas the main crack in the aged welded joint was tortuous and intersected with more creep cracks. Figure 5 also shows that, during the creep test, C diffusion also occurred in the as-welded Cr5Mo/A302 dissimilar welded joint, which had no C migration before the test, and the width of the carburized layer increased by approximately 3.3 μm. For the aged Cr5Mo/A302 dissimilar welded joint specimen, in which C diffusion and a carburized layer had already formed before the test, the rate of increase in the width of the carburized layer was slower, increasing by only approximately 2.3 μm.

Fig.3 Hardness distribution near the FL of Cr5Mo/A302 dissimilar joints after aging for different times

Fig.4 Creep rupture life comparison of Cr5Mo/A302 dissimilar joints of as-weld and aging at 650 °C for 257 h

Fig.5 Fracture morphologies of Cr5Mo/A302 dissimilar joints of as-weld (a) and aging at 650 °C for 257 h (b) after creep test at 550 °C, 100 MPa

3 Analysis and Discussion

3.1 Theoretical calculation of C diffusion

To further study C diffusion and compare it with the experimental results, Fick' s second law was used to perform a numerical analysis of C diffusion in the Cr5Mo/A302 welded joint. The C diffusion in the dissimilar welded joint is a one-dimensional, spatially non-steady diffusion problem. The expression of Fick' s second law can be written as follows[9]:

$$\frac{\partial c(x,t)}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial c(x,t)}{\partial x}\right) \tag{1}$$

where $c(x,t)$ is the concentration of element C along the diffusion direction, kg/m^3; t is the diffusion time, s; x is the diffusion distance, m; and D is the diffusion coefficient of C in the dissimilar welded joint, m^2/s.

The error-function solution of Eq. (1) is:

$$c(x,t) = \begin{cases} B_1 + B_2 \operatorname{erf}\left(\dfrac{x}{2\sqrt{D_\mathrm{b}t}}\right) & (x<0) \\ B_3 + B_4 \operatorname{erf}\left(\dfrac{x}{2\sqrt{D_\mathrm{w}t}}\right) & (x\geq 0) \end{cases} \tag{2}$$

where B_1, B_2, B_3, and B_4 are constants; D_b is the diffusion coefficient of C in the base metal, m^2/s; and D_w is the diffusion coefficient in the weld seam, m^2/s. According to Refs. [12,22,23], $D_\mathrm{w} = 3.0935 \times 10^{-17}$ m^2/s, and $D_\mathrm{b} = 3.0766 \times 10^{-18}$ m^2/s.

Because the weld metal has a certain width, and the width of the fusion zone can be neglected relative to that of the weld metal, the diffusion problem of the welded joint can therefore be simplified as a diffusion couple. Thus:

(1) At the initial moment, i.e., when $t=0$, the C contents on the two sides of the fusion line are respectively the C content c_b in the base metal and the C content c_w in the weld seam, namely:

$$c(x,t)\big|_{t=0} = \begin{cases} c_\mathrm{b} = 0.14\% & (x<0) \\ c_\mathrm{w} = 0.08\% & (x\geq 0) \end{cases} \tag{3}$$

(2) At $x = \infty$, i.e., at positions far from the fusion line, the C concentrations are respectively the C contents in the base metal and in the weld material, namely:

$$c(x,t)|_{x=\infty} = \begin{cases} c_{\mathrm{b}} = 0.14\% & (t > 0) \\ c_{\mathrm{w}} = 0.08\% & (t > 0) \end{cases} \tag{4}$$

(3) When $x = 0$, the C concentrations on the two sides of the fusion line are respectively the minimum C content in the decarburized layer of the base metal and the maximum C content in the carburized layer of the weld seam:

$$c(x,t)|_{x=0} = \begin{cases} c_{\mathrm{bmin}} & (t > 0) \\ c_{\mathrm{wmax}} & (t > 0) \end{cases} \tag{5}$$

where c_{bmin} is the minimum C content in the decarburized layer of the base metal; and c_{wmax} is the maximum C content in the carburized layer of the weld seam.

In addition, according to the equality of the diffusion fluxes and chemical potentials on the two sides of the fusion line at $x = 0$, there are:

$$J_{\mathrm{w}} = J_{\mathrm{b}} \tag{6}$$

$$\mu_{\mathrm{w}} = \mu_{\mathrm{b}} \tag{7}$$

$$J = -D\frac{\partial c}{\partial x} \tag{8}$$

$$\mu = \mu_0 + kT\ln(f_{\mathrm{c}}C_0) \tag{9}$$

where J is the diffusion flux, kg/(m$^2\cdot$s); J_{w} is the diffusion flux in the weld seam, kg/(m$^2\cdot$s); J_{b} is the diffusion flux in the base metal, kg/(m$^2\cdot$s); μ is the chemical potential, J/mol; μ_0 is the standard chemical potential, J/mol; μ_{w} is the chemical potential in the weld seam, J/mol; μ_{b} is the chemical potential in the base metal, J/mol; k is the Boltzmann constant, J/K; T is the thermodynamic temperature, K; f_{c} is the activity coefficient; and C_0 is the mass fraction of C on the two sides of the fusion line.

Combining Eqs. (2)-(9), the constants B_1, B_2, B_3, and B_4 can be obtained, and hence the C distributions on the two sides of the fusion line of the Cr5Mo/A302 dissimilar welded joint are obtained, as shown in Fig. 6. It can be seen from the figure that the widths of both the decarburized layer on the base-metal side

Fig. 6

Figure 1: Fig. 6

and the carburized layer on the weld-seam side increase with increasing aging time. A comparison of the decarburized layer and carburized layer shows that the decarburized layer has a large range, with a maximum width of about 600 μm; the change in C content is relatively gradual, and its minimum C content (0.10%) differs little from that of the Cr5Mo base metal (0.14%). The carburized layer has a maximum width of about 10 μm, but its maximum C content (2.22%) is nearly 30 times higher than the normal C content of the weld seam (0.08%).

The fitting results were compared with the microhardness measurement results of the decarburized layer and the metallographic observation results of the carburized layer; the results are shown in Fig. 7. It can be seen that the experimentally measured width-distribution patterns of the decarburized and carburized layers are relatively close to the numerical-analysis results.

3.2 Discussion of the effect of C diffusion on the creep endurance life of the joint

The high-temperature creep-damage mechanism of metallic materials is closely related to the stress level. Under high stress ($> 0.4\sigma_{0.2}$-$0.5\sigma_{0.2}$), the high-temperature creep damage of metallic materials follows a damage mechanism controlled by plasticity [24, 25]. Carbides, as high-temperature strengthening phases in metallic materials, hinder dislocation motion, thereby increasing creep strength [26]. After a decarburized zone forms in a dissimilar welded joint, the decomposition of carbides greatly reduces their hindering effect on dislocations; under the action of stress, plastic deformation is more likely to occur in the decarburized zone.

Fig. 6 Calculated carbon concentration distribution based on Fick' s law in the base metal (a) and weld seam (b) of Cr5Mo/A302 dissimilar joints after aging at 650 ℃ for different times

creep deformation, and finally fracture first occurs in the decarburized zone. Under low stress ($0.2\sigma_{0.2} \sim 0.4\sigma_{0.2}$), creep damage is a damage mechanism controlled by the nucleation of grain-boundary creep cavities[^24,^25,^27,^28]. Creep cavities first nucleate at grain boundaries, grow, coalesce into microcracks, and gradually develop into macroscopic cracks, ultimately leading to fracture. In the fracture process dominated by this mechanism, the nucleation and growth of creep cavities become the main controlling factors for fracture. Therefore, the influence of the reduction in creep strength caused by decarburization on the life of dissimilar joints is not as significant as under the plasticity-controlled mechanism. Macroscopically, as the stress level decreases, the difference in creep life between the as-welded dissimilar joint and the aged dissimilar joint becomes increasingly small.

Fig. 7

Figure 2: Fig. 7

After aging treatment, the OM image of creep cracks in the decarburized layer of the Cr5Mo/A302 dissimilar welded joint tested at 550 °C and 80 MPa is shown in Fig. 8. It can be seen that, under low-stress conditions, a large number of creep cavities appear at the grain boundaries in the decarburized layer, and cracks extend along the cavities, indicating that under the stress condition of 80 MPa, the nucleation and growth of creep cavities have become the dominant factors governing damage in the Cr5Mo/A302 dissimilar welded joint.

In addition, during the creep rupture test, due to the effect of high temperature, C diffusion also occurs in the dissimilar joint; moreover, the lower the stress level and the longer the test time, the higher the degree of C diffusion. Since C diffusion follows a parabolic law, it can be inferred that when the time is sufficiently long, the degrees of C diffusion in the two joints will increasingly tend to be consistent. The damage caused by C diffusion to the dissimilar joint will also gradually tend to be consistent, and thus the creep lives will also tend to be consistent.

To quantitatively characterize the influence of already-occurred C diffusion on the life of Cr5Mo/A302 dissimilar welded joints, and to determine the functional relationship between this influence and the stress level, the C-diffusion impact factor S is defined to characterize the degree to which the already-occurred C migration affects the joint life:

$$S = \frac{\lg T_0 - \lg T_\mathrm{d}}{\lg T_0} \tag{10}$$

where T_0 is the rupture life of the as-welded joint at a given stress level, h; T_d is the rupture life of the joint after aging treatment at the same stress level, h. The smaller S is, the smaller the influence of the already-occurred C diffusion on the joint life; when $S = 0$, it indicates that the already-occurred C diffusion has no influence on the joint life.

The relationship between the C-diffusion impact factor S and stress σ is shown in Fig. 9. It can be seen that, as the stress σ decreases, the C-diffusion impact factor S decreases rapidly and follows a quadratic functional relationship. The functional relationship is:

$$\sigma = 72.9884 + 554.8882 \times S - 710.4042 \times S^2 \tag{11}$$

From Eq. (11), when $S = 0$, $\sigma = 72.99$ MPa, that is, when the stress is [[unclear: text continues on next page]].

Fig. 8

Figure 3: Fig. 8

Fig. 9

Figure 4: Fig. 9

Fig. 7 Comparison of decarburized zone (a) and carbon-rich zone (b) widths between calculated and experimental results of Cr5Mo/A302 dissimilar joints after aging at 650 °C for different times (t—time, h—thickness)

Fig. 8 Fracture morphology of Cr5Mo/A302 dissimilar joint aged at 650 °C for 257 h after creep test at 550 °C, 80 MPa

Fig. 9 Relationship of stress and carbon diffusion impact factor S

when it decreases under load to 72.99 MPa (36% of the yield strength), the lifetimes of the two types of joints are the same. This means that, at this stress level, the C diffusion caused by aging treatment has no effect on the long-term life of the joint.

As one form of damage in metallic materials, C diffusion may have a considerable effect on material properties and must be evaluated under different conditions (such as different stress levels); otherwise, very large errors may result.

4 Conclusions

(1) In Cr5Mo/A302 dissimilar welded joints at high temperature, C diffuses from the base metal into the weld. A carburized layer appears on the weld side near the fusion line, while a decarburized layer appears on the base-metal side. The C-diffusion behavior in this type of joint can be calculated using the error-function solution of Fick' s second law, and the calculated results are relatively close to the measured results.

(2) Because the C content in the decarburized layer decreases, the creep fracture resistance governed by plasticity in this region is reduced. C diffusion has a relatively large effect on the long-term life of Cr5Mo/A302 dissimilar welded joints under high stress, and may shorten the life by several times.

(3) As the stress level decreases, owing to changes in the fracture mechanism, the proportion of damage caused by the pre-existing C diffusion in the joint within the overall fracture damage gradually decreases. The difference in life between the as-welded and aged joints gradually diminishes, until it becomes essentially the same.

(4) By introducing the C-diffusion influence factor S, the sensitivity of Cr5Mo/A302 joints with pre-existing C diffusion under different stress levels was characterized. The sensitivity of welded joints to pre-existing

C diffusion decreases as the stress decreases. The C-diffusion influence factor S and the stress σ satisfy a quadratic functional relationship. When the stress level decreases to below 36% of the yield strength, the C diffusion that has already occurred has no effect on the life of the welded joint.

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(Responsible editor: Luo Yanfen)

Note: Figure translations are in progress. See original paper for figures.