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Estimation of the J-resistance curve for Cr2Ni2MoV steel using the modified load separation parameter S_{pb} method*

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Abstract: Based on load separation theory, the load separation parameter S_{pb} method is an effective approach for estimating the J-resistance curve from records of load versus displacement directly, using one sharp cracked specimen and an additional reference blunt cracked specimen. However, the effect of the reference blunt cracked specimen on J-resistance determination was not explicitly considered in past work. In this paper, a modified load separation parameter S_{pb} method was developed to eliminate this effect, and then a unique estimation of instantaneous crack length for one sharp cracked specimen could be obtained. Furthermore, a forced blunting calibration method was also adopted to determine the instantaneous crack length in the load inseparable region, referring to a normalization method. Experiments on steam turbine rotator steel Cr2Ni2MoV were carried out to estimate J-resistance curves using an unloading compliance method. By removing unload and reload data from load-displacement records, the J-resistance curve for the same sharp cracked specimen was estimated using the modified separation parameter S_{pb} method. The results indicate that the modified S_{pb} method completely eliminates the effect of the reference blunt cracked specimen on the instantaneous crack length determination of the sharp cracked specimen. However, different J-resistance curves in a small range of crack extension are present when different blunting coefficients are used in the blunting line equation. The J-resistance curve obtained from the modified S_{pb} method agrees well with that obtained from the compliance method.

Key words: Load separation, J-resistance curve, Separation parameter S_{pb}, Blunt cracked specimen, Forced blunting calibration
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1 Introduction

In fracture mechanics, J-integral is the most important parameter representing the fracture toughness of ductile materials. Under stable crack propagation conditions, ductile fracture toughness J_c at crack initiation can be estimated from the resistance curve of the J-integral versus crack extension Δa. The key technique in this process is determination of crack extension Δa. The multiple specimen method and the single specimen unloading compliance method are commonly applied. For the multiple specimen method, several specimens are loaded at different load levels, and then the specimens are broken to measure crack length via a microscope device. However, this method requires considerable materials and is time-consuming, with no consideration of data dispersion. For the unloading compliance method, the crack length of the specimen can be indirectly determined by the unloading compliance. The precision of the crack length measurement strongly relies on the degree of the linear elastic response of materials. Additionally, unfavorable results may be obtained for higher toughness materials using the compliance method.

Since the load separation theory was proposed (Ernst *et al.*, 1979; 1981), J-resistance curves have been directly estimated from load-displacement records. Based on the load separation theory, a normalization method was firstly proposed by Herrera and Landes (1988). In this method, load is normalized by a geometry function and then a deformation

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function can be expressed as the relationship between the normalized load and the normalized plastic displacement. To determine the instantaneous crack length during loading, the deformation function can be described by a power function (Landes and Herrera, 1988) with two calibration points or by LMN function (Landes *et al.*, 1991) with three calibration points, where load, displacement, and crack length must be known simultaneously. Two of these points are easy to determine from fracture surfaces. This method is successfully applied for some metal and non-metal materials (Dubey *et al.*, 1999; Cassanelli *et al.*, 2001; Morhain and Velasco, 2001; Dzugan and Viehrig, 2004; Baldi and Riccò, 2005; Zhu and Joyce, 2007; Varadarajan *et al.*, 2008; Zhu, 2009; Zhu *et al.*, 2009).

A new method, named the load separation parameter S_{pb} method (Wainstein *et al.*, 2003; 2004; Salazar and Rodríguez, 2008), which uses only one sharp cracked specimen and an additional blunt cracked specimen to obtain the *J*-resistance curve. Two calibration points as initial and final crack lengths can be physically measured on the fracture surface of the broken specimen. However, only one calibrated blunt cracked specimen per material was adopted (Wainstein *et al.*, 2003; 2004; Salazar and Rodríguez, 2008); thus, the effect of the blunt cracked specimen on this method was not discussed clearly. This paper proposes a modified load separation parameter S_{pb} method to eliminate this effect, experiments of *J*-resistance curve estimation on steam turbine rotator steel Cr2Ni2MoV are performed and the validity of the modified method is completely certificated.

2 Theoretical background

2.1 Load separation theory

According to the load separation theory, the load P can be expressed as the product of a geometry function $G(a/W)$ (Sharobeam and Landes, 1991) and a deformation function $H(V_{\mathrm{P}}/W)$:

$$P = G\left(\frac{a}{W}\right)\cdot H\left(\frac{V_{\mathrm{P}}}{W}\right) = WB\left(\frac{b}{W}\right)^{m}\cdot H\left(\frac{V_{\mathrm{P}}}{W}\right), \quad (1)$$

where a is the crack length, W is the specimen width, B is the specimen thickness, and V_{P} denotes the plastic part of crack opening displacement, and m is a material constant. Sharobeam and Landes (1991) introduced a separable parameter S_{ij}, which is defined as the ratio of load of two blunt cracked specimens with different crack lengths, a_{i} and a_{j}, at the same plastic displacement V_{P},

$$S_{\mathrm{ij}} = \left.\frac{P_{\mathrm{i}}(a_{\mathrm{i}},V_{\mathrm{P}})}{P_{\mathrm{j}}(a_{\mathrm{j}},V_{\mathrm{P}})}\right|_{V_{\mathrm{P}}} = \left.\frac{G\left(\frac{a_{\mathrm{i}}}{W}\right)\cdot H\left(\frac{V_{\mathrm{P}}}{W}\right)}{G\left(\frac{a_{\mathrm{j}}}{W}\right)\cdot H\left(\frac{V_{\mathrm{P}}}{W}\right)}\right|_{V_{\mathrm{P}}} = \frac{G\left(\frac{a_{\mathrm{i}}}{W}\right)}{G\left(\frac{a_{\mathrm{j}}}{W}\right)} = \text{constant}. \quad (2)$$

Thus, S_{ij} is independent of the deformation function and depends only on the geometry function. For a stationary crack, the geometry function remains constant, and so does the S_{ij} parameter over the whole domain of the plastic displacement.

2.2 Load separation parameter S_{pb} method

To study the load separation property for the growing crack specimen, another parameter S_{pb} is proposed (Sharobeam and Landes, 1993):

$$S_{\mathrm{pb}} = \left.\frac{P_{\mathrm{p}}}{P_{\mathrm{b}}}\right|_{V_{\mathrm{P}}} = \left.\frac{G\left(\frac{a_{\mathrm{p}}}{W}\right)\cdot H\left(\frac{V_{\mathrm{P}}}{W}\right)}{G\left(\frac{a_{\mathrm{b}}}{W}\right)\cdot H\left(\frac{V_{\mathrm{P}}}{W}\right)}\right|_{V_{\mathrm{P}}} = \left.\left(\frac{a_{\mathrm{p}}}{a_{\mathrm{b}}}\right)^{m}\right|_{V_{\mathrm{P}}}, \quad (3)$$

where subscripts p and b represent the sharp cracked specimen and the blunt cracked specimen, respectively. The parameter S_{pb} remains constant while no crack growth occurs in the sharp cracked specimen. Later, the parameter S_{pb} may vary if the crack starts to propagate, and the last point of S_{pb} versus V_{P} records corresponds to final crack length. The initial and final crack lengths can be measured on the fracture surface of the broken sharp cracked specimen. Thus, the two points may be chosen as calibration points to determine parameter m in Eq. (3). In addition, when the crack length of the sharp cracked specimen performs the same value as that of the reference blunt cracked specimen, S_{pb} equals to 1, and it can be chosen as the third theoretical calibration point. If exponent m is determined, the instantaneous crack length of the sharp cracked specimen can be estimated from

$$a_{\mathrm{p}} = a_{\mathrm{b}} (S_{\mathrm{pb}})^{1/m}. \tag{4}$$

When the crack length corresponding to each point of load-displacement records is determined, the *J*-integral can be calculated by (ASTM E1820-08a, 2008)

$$\begin{cases} J_{(i)} = \dfrac{K_{(i)}{}^2 (1-\nu^2)}{E} + J_{\mathrm{p}(i)}, \\ J_{\mathrm{p}(i)} = \left[J_{\mathrm{p}(i-1)} + \dfrac{\eta_{(i-1)}}{B_N b_{(i-1)}} (A_{\mathrm{P}(i)} - A_{\mathrm{P}(i-1)}) \right] \\ \qquad \times \left[1 - \dfrac{\gamma_{(i-1)}}{b_{(i-1)}} (a_{(i)} - a_{(i-1)}) \right], \end{cases} \tag{5}$$

where K is a stress intensity factor, A_{P} is the plastic work, B_{N} is the net thickness of sharp cracked specimen, b is the length of remaining ligament, and $\eta_{(i-1)}=2+0.522\times b_{(i-1)}/W$, $\gamma_{(i-1)}=1+0.76\times b_{(i-1)}/W$.

3 Experimental

A sharp cracked compact tensile (CT) specimen was employed to estimate the *J*-resistance curve for steam turbine rotator steel Cr2Ni2MoV using the unloading compliance method. By removing cyclic data from the load-displacement records, the remaining data were re-treated using the load separation parameter S_{pb} method. To study the load separation property of this material, another four blunt cracked specimens were tested. For the blunt cracked specimen, there is a blunt notch at the crack tip, whose curvature radius is 1.5 mm with a crack length remains constant under loading. The crack lengths of the blunt cracked specimens are 32.5, 35.0, 37.5, and 40.0 mm, i.e., the values of a/W of these four blunt cracked specimens are 0.65, 0.70, 0.75, and 0.80, respectively. All tests were carried out on an electromechanical testing machine (MTS 809, 250 kN, MTS system corporation, UAS) at room temperature and under displacement control at a speed of 0.02 mm/s. The crack opening displacement along the loading line was measured by a standard crack opening displacement extensometer MTS 632.02F-20 (MTS system corporation, USA) with full range of 4 mm and initial gage length of 5 mm.

4 Results and discussion

4.1 Load separation property

Fig. 1 gives the records of load versus loading line crack opening displacement for the sharp cracked specimen using the compliance method. In Fig. 2, monotonic loading records for sharp cracked specimen were picked up from the results of the compliance method. In addition, monotonic load-displacement records for the blunt cracked specimens are also shown. Fig. 3 shows the properties of separation parameter S_{ij} for different blunt cracked specimens, where the blunt cracked specimen with the largest crack length has been chosen as the reference specimen. The plots show that S_{ij} remains constant through the whole range of plastic displacement V_{P} except for a limit region at the beginning of the plastic displacement. If choosing the other blunt cracked specimens as the reference specimens, similar results may be observed. Thus, load P is separable for this material and it can be expressed as the product of two separate functions, as proposed in Eq. (1).

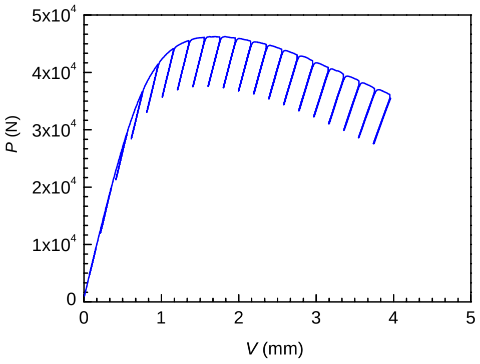

Fig. 1 *P*-*V* curve obtained from compliance method

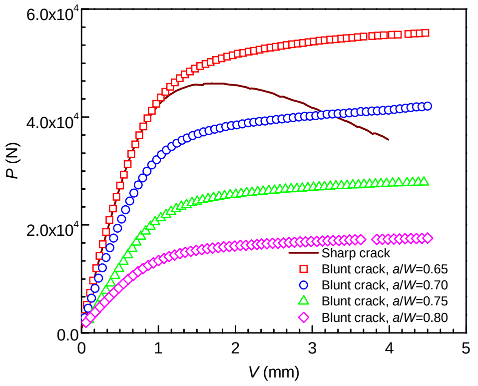

Fig. 2 *P*-*V* curves of the specimens with blunt crack and sharp crack

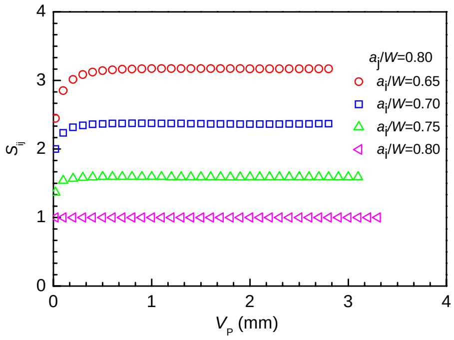

Fig. 3 Properties of separation parameter S_{ij} for blunt cracked specimens

4.2 Effect of the choice of reference blunt cracked specimen

Fig. 4 shows the curve of separation parameter S_{pb} versus plastic displacement V_P with different reference blunt cracked specimens. At the beginning of plastic displacement V_P, S_{pb} increases quickly with increasing V_P, which means that load separation assumption for sharp cracked specimen is not satisfied in this region. Then the parameter S_{pb} remains constant in a limited region, which identifies that load is separable and no crack propagation occurs. Finally, S_{pb} starts to reduce while V_P exceeds the point of crack growth onset.

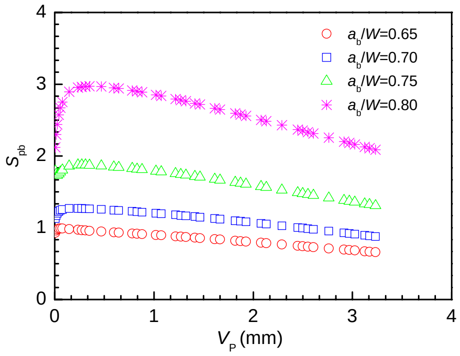

Fig. 4 Experimental curves of S_{pb} versus V_P

However, it must be noted that four different points of crack growth onset are presented based on these four different reference blunt cracked specimens. As shown in Table 1, the maximum difference of V_P at the point of crack growth onset is close to 0.3 mm. It means that four different curves of instantaneous crack length versus plastic displacement V_P may be obtained for the same sharp cracked specimen, so the J-resistance curve estimation may also be affected by the reference blunt notched specimen.

Table 1 The values of V_P at the point of crack growth onset for different blunt cracked specimens

Blunt notch length, a_b/W	V_P (mm)	
	Original S_{pb} method	Modified S_{pb} method
0.65	0.0652	0.616
0.70	0.233	0.655
0.75	0.264	0.655
0.80	0.351	0.631

As mentioned above, the load separation assumption cannot be satisfied in a limited region at the beginning of the plastic displacement. We think that this limited region may be different for different blunt cracked specimens, and it leads to different points of crack growth onset in the records of S_{pb} versus V_P for the same sharp cracked specimen. Assuming a referenced yield limit load P_s (Hu and Albrecht, 1991):

$$P_s = \frac{Bb_0^2\sigma_s}{2W + a_0}, \tag{6}$$

where P_s is less than the maximum load in the load-plastic displacement records. It is well-known that crack propagation generally occurs at the point when load is close but less than the maximum load. Then the plastic displacement can be treated as

$$V' = (V_P - V_{Ps}) / W, \tag{7}$$

where V_{Ps} denotes the value of plastic displacement corresponding to P_s in the load-displacement records. It must be noted that the load cannot be subtracted by P_s. By re-treating load-displacement records for blunt cracked specimens, load separation properties are shown in Fig. 5, the separation parameter S_{ij} remains constant in the whole range of the modified displacement V'. Fig. 6 shows the curves of S_{pb} versus V' for different reference blunt cracked specimens. The parameter S_{pb} increases with increasing V' at the beginning, which indicating that no crack growth occurs. More importantly, the very close plastic displacement corresponding to crack growth onset can be obtained from the modified S_{pb}-V' records. As shown in Table 1, the difference of plastic displacement V_P at these points is less than 0.05 mm; thus, a unique curve of crack length versus displacement may be obtained for the same sharp cracked specimen.

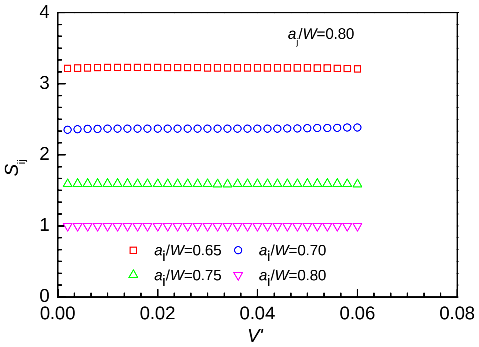

Fig. 5 Properties of S_{ij} with the modified method

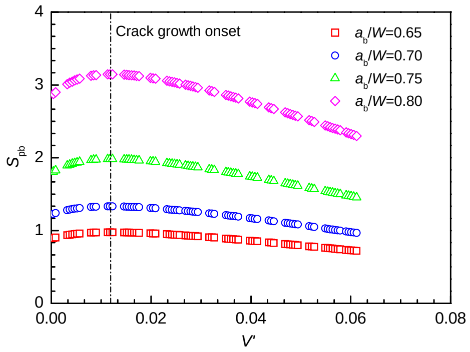

Fig. 6 Properties of S_{pb} with the modified method

Fig. 7 shows the curves of instantaneous crack length versus total displacement using the original load separation parameter S_{pb} method with different reference blunt cracked specimens. Unfortunately, different instantaneous crack length estimations for the same sharp cracked specimen are presented with different reference blunt cracked specimens. Fig. 8 presents the estimation of instantaneous crack length for sharp cracked specimen based on the modified S_{pb} method. The curves of instantaneous crack length versus V_P are consistent with each other referenced by different blunt cracked specimens. Additionally, instantaneous crack length estimated from the modified S_{pb} method is in agreement with that obtained from the compliance method.

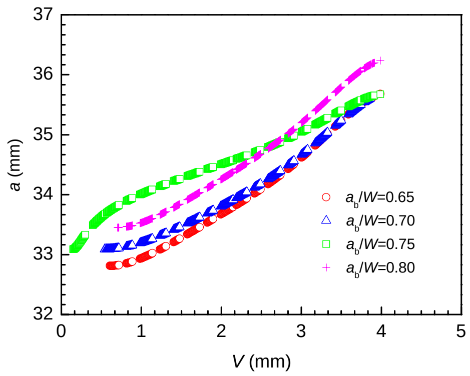

Fig. 7 Estimation of instantaneous crack length based on original S_{pb} method with different blunt cracked specimens

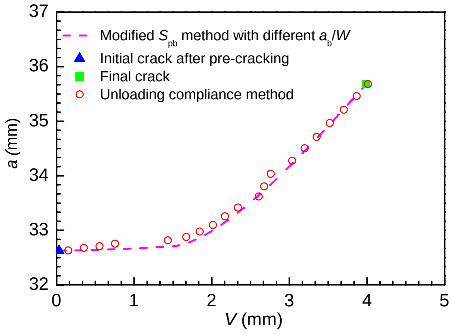

Fig. 8 Estimation of instantaneous crack length by modified S_{pb} method and compliance method

As shown in Fig. 6, the separation parameter S_{pb} remains constant within a limit range of crack opening displacement, which indicates that no crack growth is occurring; thus, the initial crack length after pre-cracking can be chosen as one of the calibration points. However, a problem of how to deal with the estimation of crack length in the load inseparable region is present. Actually, crack blunting may happen before crack growth. Initial crack length after pre-cracking and final crack length are conveniently measured on the fracture surface of a broken specimen, but the blunting crack extension is difficult to determine because of unclear boundary between the crack blunting zone and the real crack growth zone on the fracture surface. Referring to the normalization method, a forced blunting crack length can also be adopted as the calibration point, instead of the initial crack length after pre-cracking for the modified S_{pb} method. The forced blunting crack length can be obtained:

$$a_{b_i} = a_0 + \frac{J(P_i, V_i, a_0)}{\varphi(\sigma)}, \tag{8}$$

where a_0 is the initial crack length after pre-cracking, and $\varphi(\sigma)$ is the blunting coefficient of blunting line equation. Two types of blunting line equations are commonly recommended by different ductile fracture toughness test standards. In ASTM E1820 series standards, the blunting line equation is given by

$$J = 2\sigma_{\mathrm{Y}} \cdot \Delta a, \qquad (9)$$

where σ_{Y} is the flow stress, and is generally expressed as the average of yield strength and tensile strength. Thus, the function $\varphi(\sigma)$ in Eq. (8) can be replaced by $2\sigma_{\mathrm{Y}}$. However, in the British standards BS7448-1997 and ISO standards ISO 12135-2002, the blunting line equation is recommended as

$$J = 3.75\sigma_{\mathrm{b}} \cdot \Delta a, \qquad (10)$$

where σ_{b} is the tensile strength. Thus, the function $\varphi(\sigma)$ can be replaced by $3.75\sigma_{\mathrm{b}}$.

Using the two types of forced blunting calibration points as mentioned above, Fig. 9 gives the *J*-resistance curves with different reference blunt cracked specimens. It is evidently shown that the effect of reference blunt cracked specimen on the determination of *J*-resistance curves for the sharp cracked specimen is completely eliminated by using the modified S_{pb} method. However, different *J*-resistance curves in a small range of crack extension are present when different blunting coefficients in Eq. (8) are used. The *J*-resistance curves calibrated using Eq. (9) are lower than those calibrated using Eq. (10), when the crack extension is less than 1 mm. And these curves are consistent when crack extension exceeds 1 mm. The *J*-resistance curve obtained from the compliance method is closer to the curves calibrated using Eq. (9) with different reference blunt cracked specimens. It indicates that the real blunting behavior of the material used in this study can be approximately described by Eq. (9).

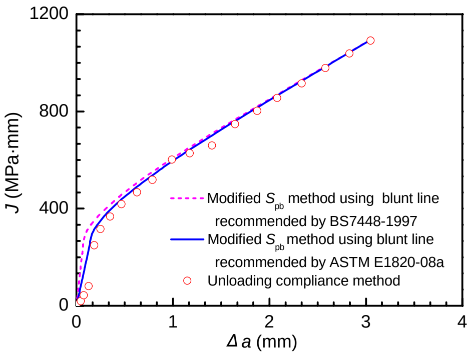

Fig. 9 *J*-resistance curves estimated by the compliance method and the modified S_{pb} method

5 Conclusions

The load inseparable property for a blunt cracked specimen at the beginning of plastic displacement has an evident influence on the point of crack growth onset. Thus, several different and unreasonable crack length measurements may be obtained for the same sharp cracked specimen based on different reference blunt cracked specimens. A modified separation parameter S_{pb} method has been proposed by re-treating P-V_{P} records. Consequently, the effect of a reference blunt cracked specimen on the estimation of instantaneous crack length can be completely eliminated. Additionally, a force blunting calibration method referring to a normalization method is adopted in the modified S_{pb} method. Using the modified S_{pb} method, *J*-resistance curves agree well with those obtained from the compliance method.

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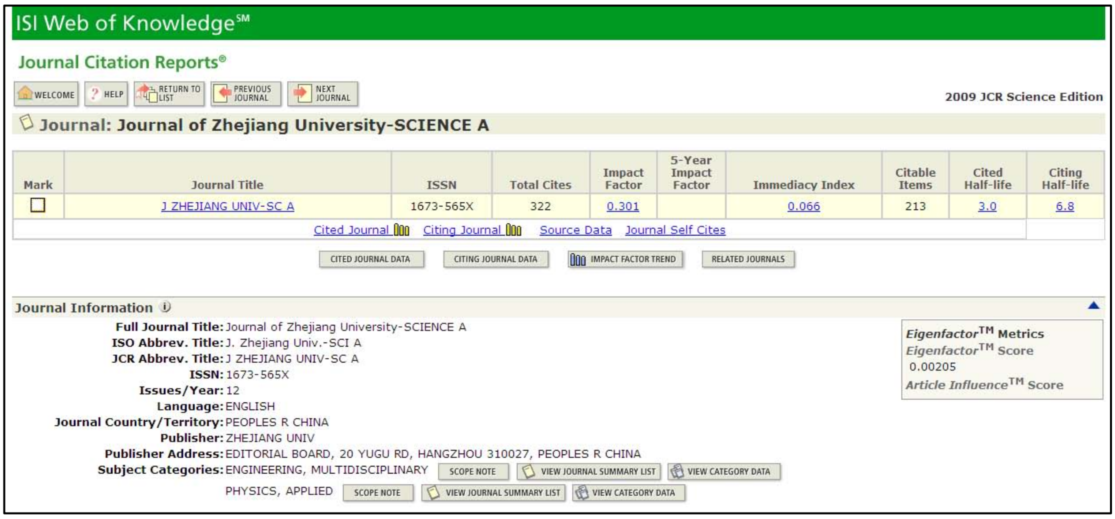

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