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Research Article

Corrosion Failure of AISI4340 Steel in Oxygen-Containing Aqueous Chloride Solution

Ping Zhang,[1] Yafei Shi,[2] Hanqing Zhao,[2] Fulin Zhang,[2] Guoqiang Zhang,[1] and Sixian Rao[2]

[1]*College of Civil Engineering, Hunan University, Changsha 410082, China*
[2]*School of Mechanical Engineering, Anhui University of Technology, Ma'anshan 243002, China*

Correspondence should be addressed to Sixian Rao; snowdrio@126.com

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Stress corrosion cracking behavior of 4340 steel in oxygen-containing or chloride containing aqueous solution was researched, the tensile experiment results indicated 100°C deaerated distilled water, the rupture of 4340 steel mainly belongs to ductile fracture, the addition of oxygen or chloride would increase the SCC tendency of 4340 steel and transformed the rupture mechanism from ductile fracture to brittle rupture, the existence of oxygen or chloride would decrease K_{ISCC} of 4340 steel in 100°C aqueous solution slightly, the simultaneous action of oxygen and chloride existed, and the simultaneous action would further increase the SCC tendency of 4340 steel in aqueous solution.

1. Introduction

AISI4340 steel was widely used as the material of super high pressure tubular reactor due to its high mechanical strength [1, 2], while 4340 was susceptible to stress corrosion cracking (SCC) or corrosion fatigue (CF) [3–5]. When SCC occurred on the super high pressure tubular reactor pipes, the leakage would cause serious failure accident [6–10]. In AISI4340 super high pressure tubular reactor, the oxygenated and chlorinated water existed, and the main failure mode may be SCC (Stress Corrosion Cracking) or CF (Corrosion Fatigue) induced by oxygen or chloride [11–15], of which failure mechanism played the dominating role needed to be confirmed, as the main failure mechanism determination was related to the appropriate treatment measures to reduce failure risk [6].

2. Experiments and Materials

2.1. Materials Processing and Testing Methods. AISI4340 steel was selected as the experimental material; the state of 4340 was annealing. There is no internal force or residual stress inside the material after heat treatment. The specimens were cut from commercial steel sheet along rolling direction by wire cutting. Then, the surface of the sample is ground by grinding machine to smooth the surface to eliminate the surface irregularity produced by wire cutting, and the final surface roughness is 3.2. The chemical compositions of 4340 were listed in Table 1. In slow rate tensile tests round bar specimens were used, in SCC experiments CT specimens were used, and the size of round bar and notch specimens were listed in Figures 1 and 2, respectively.

Experiments were carried out on CORTEST slow rate tensile stress corrosion testing machine, all the experiment temperature was controlled at 100°C, and the experimental condition was listed in Table 2.

The morphology of the specimens was recorded by Nano-430 thermal field emission scanning electron microscope (SEM) and the chemical constitutions of the corrosion products were analyzed by EDS.

3. Experiments Results and Discussion

3.1. Analysis on the Corrosion Morphology of 4340 during Tensile Experiments. The tensile rate of the round bar specimens was controlled at 4.5×10^{-5}mm/s, and the strain was

Table 1: Chemical composition of AISI4340 (Mass%).

element	C	Si	Mn	Cr	Ni	Mo	S	P	Cu	Fe
content	0.4	0.2	0.5	0.9	1.5	0.2	≤0.025	≤0.025	≤0.25	balance

Table 2: The experimental condition of the specimens.

Experiment condition	Concentration of Cl^-	Concentration of oxygen	temperature
I	0	0	100°C
II	0.1mol/l	0	100°C
III	0	5mg/l	100°C
IV	0.1mol/l	5 mg/l	100°C

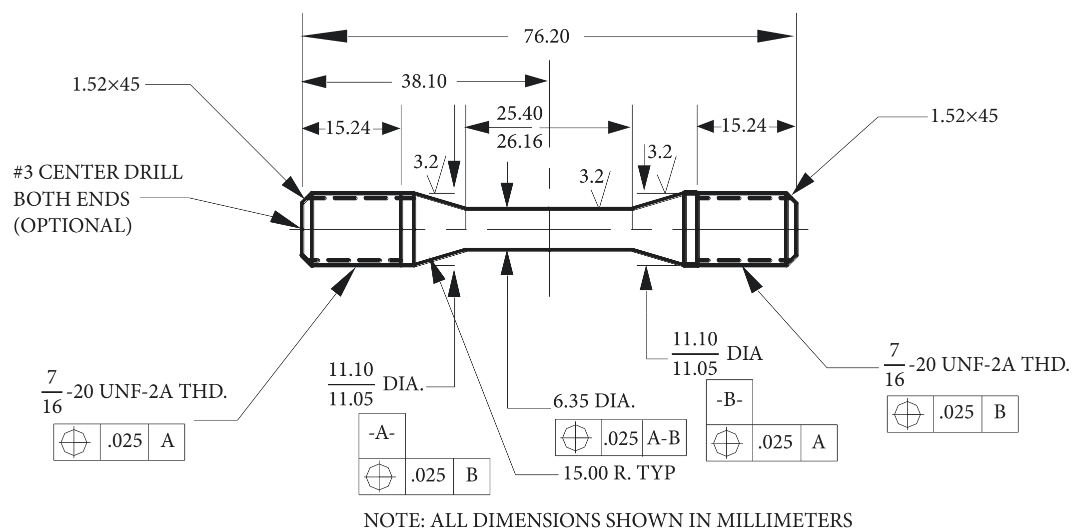


Figure 1: Round bar specimen used in the tensile experiments (all dimensions are in millimeters).

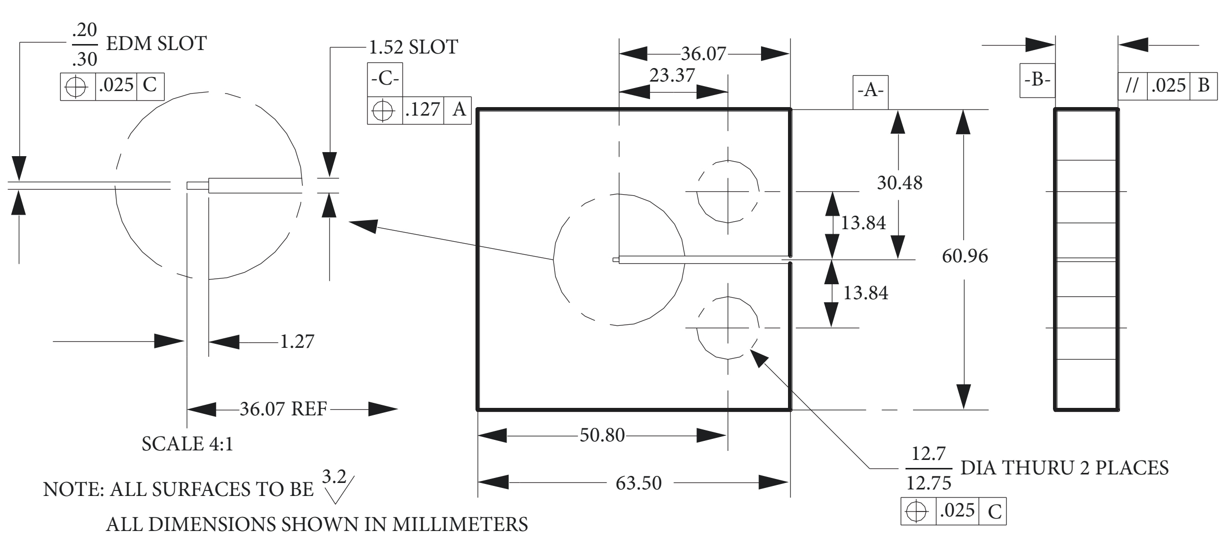


Figure 2: CT specimens used in the SCC experiments (all dimensions are in millimeters).

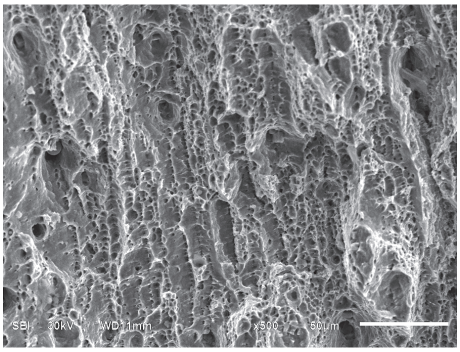


Figure 3: Fracture morphology of 4340 steel in 100°C deaerated distilled water.

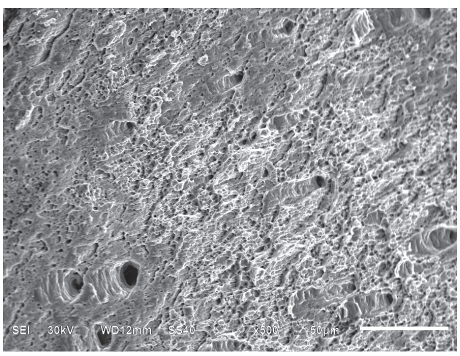


Figure 4: Fracture morphology of 4340 steel in 100°C deoxygenated 0.1mol/L chloride aqueous solution.

kept increasing until the 4340 round bar tensile specimens ruptured.

Firstly the tensile experiments were carried out in deaerated distilled water at 100°C (condition I); after experiments the specimens were taken out and the morphology of the fracture was analyzed (shown in Figure 3), large number of small dimples existed on the fracture, and this fact indicated that the fracture of 4340 steel in distilled water mainly belonged to ductile fracture [11].

To uncover the influence of Cl^- on the SCC of 4340 steel in hot water, experiments were carried out in 0.1mol/L NaCl deaerated distilled water (condition II). After the experiments the fracture morphology was observed (shown in Figure 4). On the fracture a lot of dimples still existed in some locations, but the dimples became more small; most of the fracture was quite smooth. This fact indicated that in 0.1mol/L NaCl deaerated distilled water the SCC tendency of 4340 steel increased obviously [16], but some ductile fracture characteristics still existed. The experimental results are basically consistent with [16].

The influence of oxygen on the SCC of 4340 steel in 100°C water (condition III) was also researched. After the specimens were taken out, some tawny corrosion products on the fracture could be observed; EDS analysis proved that those corrosion products belonged to oxides of 4340 steel (shown in Figure 5). After the corrosion products were removed the fracture morphology could be observed (shown in Figure 6); large number of cleavage facets and tear ridges on the fracture proved that the fracture of 4340 steel in oxygen-containing distilled water at 100°C belonged to quasi-cleavage fracture [17, 18]. This fact indicated that the existence of 5mg/L oxygen transformed the fracture of 4340 steel from ductile fracture to brittle fracture completely. With contrast to the corrosion morphology in pure 0.1mol/L NaCl aqueous solution, the influence of oxygen was more obvious.

The final experiments were carried out in oxygen-containing 0.1mol/L chloride solution at 100°C (condition IV), after the specimens were taken out, tawny corrosion products could also be observed, EDS analysis indicated that the corrosion products were consisted by oxides and chlorides (shown in Figure 7), and this fact indicated that Cl^- participated in the corrosion process [16, 19]. After the corrosion products were removed, the fracture morphology could be observed.

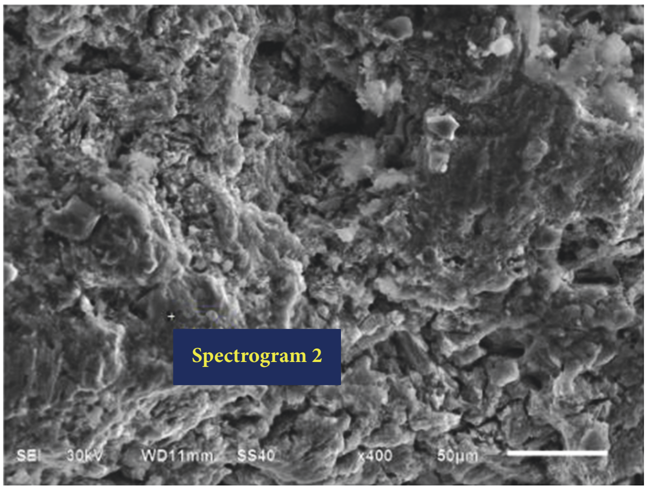
The fracture surfaces showed typical quasi cleavage river patterns, the river patterns originated from the inclusions in the grains (shown in Figure 8), and only on some specific spots of the fracture a small quantity of small dimples could be observed. Moreover considering that the fracture was quite smooth and no obvious necking occurred on the 4340 specimen, it was confirmed that brittle rupture occurred.

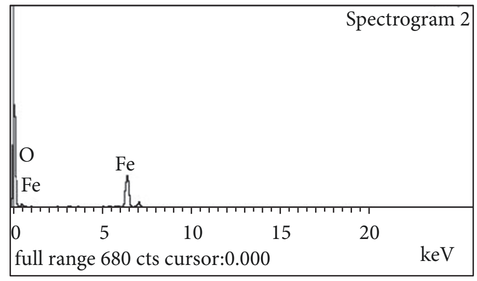
It could be concluded that the fractures of 4340 steel in deaerated distilled water (condition I) belonged to ductile rupture completely, the addition of 0.1mol/L chloride (condition II) increased the brittle rupture tendency, but some ductile fracture characteristics still existed; while addition of 5mg/L oxygen (condition III) could transform the fracture to brittle fracture completely, from the fracture morphology analysis the influence of 5mg/L oxygen was more obvious; when both chloride and oxygen existed (condition IV), the interaction of chloride and oxygen could further increase the brittle rupture tendency.

In high temperature water, the existence of oxygen could promote the formation of oxide film, under high tensile load, the oxide film broke down, and freshly exposed metal would act as anode and be oxidized repeatedly. Once crack is initiated, the stress concentration in the crack tip would aggravate the process above and increase the crack propagation [20], until brittle rupture occurred. Chloride induced brittle rupture had been discussed in many reference [15, 18], when both oxygen and chloride existed, the chloride would induce both corrosion and oxidization of freshly exposed metal repeatedly and further increase the crack propagation.

3.2. Crack Propagation of 4340 Steel under Different Aqueous Solution during SCC Experiments. To uncover the influence of oxygen and Cl^- on the SCC behavior of 4340 in high temperature aqueous solution, SCC experiments were carried out on the CT specimens, during the experiments the crack propagation were recorded, and the $d\alpha/dt$ curve of 4340 in the four aqueous solutions was listed in Figure 9.

From Figure 9 it was confirmed that the highest values of $d\alpha/dt$ were reached in deaerated distilled water; when oxygen or Cl^- existed, the crack growth rate within the plateau region decreased. It should be noticed that in deaerated distilled water the SCC growth curve was different from the curves





element	Weight percent	Atom percent
O K	15.26	38.60
Fe K	84.74	61.40
total	100.00	

Figure 5: The oxides on the fracture of 4340 in 100°C oxygen-containing distilled water.

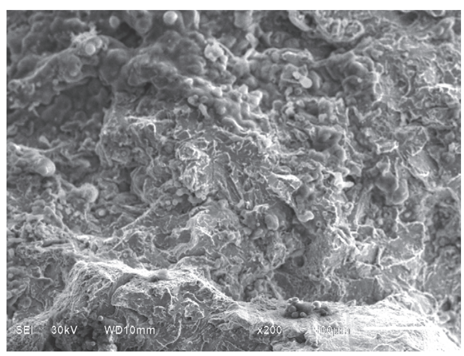
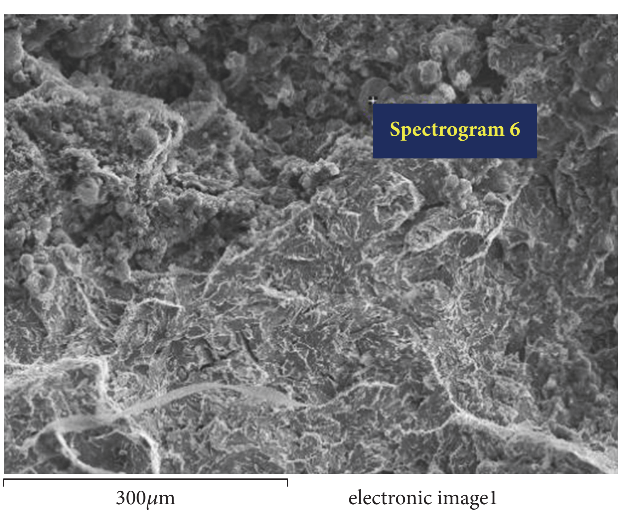
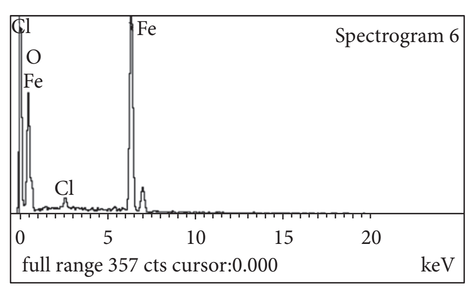


Figure 6: Fracture morphology of 4340 in 100°C oxygen-containing distilled water.





element	Weight percent	Atom percent
O K	44.33	73.28
Cl K	1.35	1.00
Fe K	54.32	25.72
total	100.00	

Figure 7: The oxides on the fracture of 4340 in 100°C oxygen-containing 0.1mol/L chloride aqueous solution.

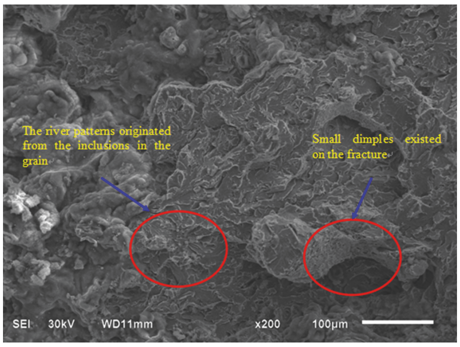


Figure 8: Fracture morphology of tensile specimen of 4340 steel.

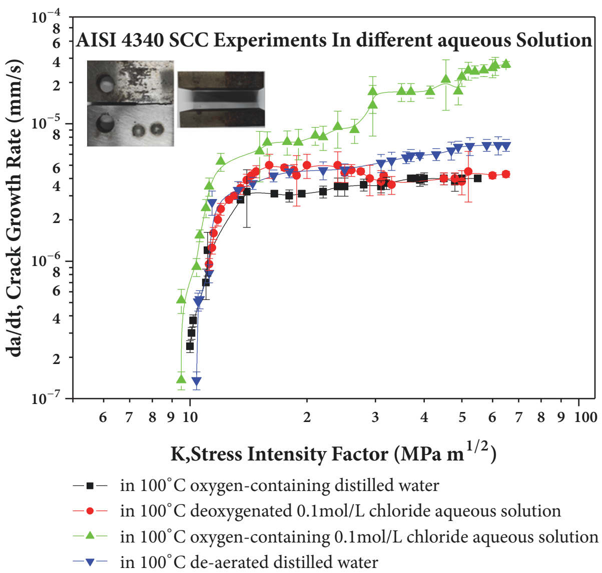


Figure 9: dα/dt of 4340 steel in different aqueous solutions.

in other aqueous solution by the absence of the pronounced plateau in stage II; this fact indicated that in deaerated distilled water the velocity of crack extension was dependent on the stress intensity in all three stages of crack growth; similar researches could observe the same phenomenon [15, 18], while when oxygen or Cl^- existed the pronounced plateau of stage II existed.

From Figure 9 K_{ISCC} four kinds of aqueous solution could be confirmed, and deaerated distilled water K_{ISCC} of 4340 was about 11MPa·m$^{1/2}$, which was almost equal to the value of K_{ISCC} in 0.1mol/l chloride aqueous solution; oxygen-containing distilled water K_{ISCC} decreased, and the value was about 10MPa·m$^{1/2}$; when both oxygen and chloride existed, K_{ISCC} decreased to 9MPa·m$^{1/2}$ furtherly [5, 15]. The decrease of K_{ISCC} would increase in SCC tendency of 4340 steel.

4. Conclusion

From the experiment results it could be confirmed that both oxygen and chloride could increase the SCC tendency of 4340 steel. The influence of 5mg/l oxygen on K_{ISCC} was almost equal to the influence of 0.1mol/l Cl^-, but the accurate influence on the SCC behavior of 4340 depended on the concentration of oxygen and chloride, when both oxygen and chloride existed, simultaneous action of oxygen and Cl^- existed, and the simultaneous action would further increase the SCC tendency of 4340 steel in aqueous solution, so in high temperature water, the concentration of both oxygen and Cl^- should be controlled.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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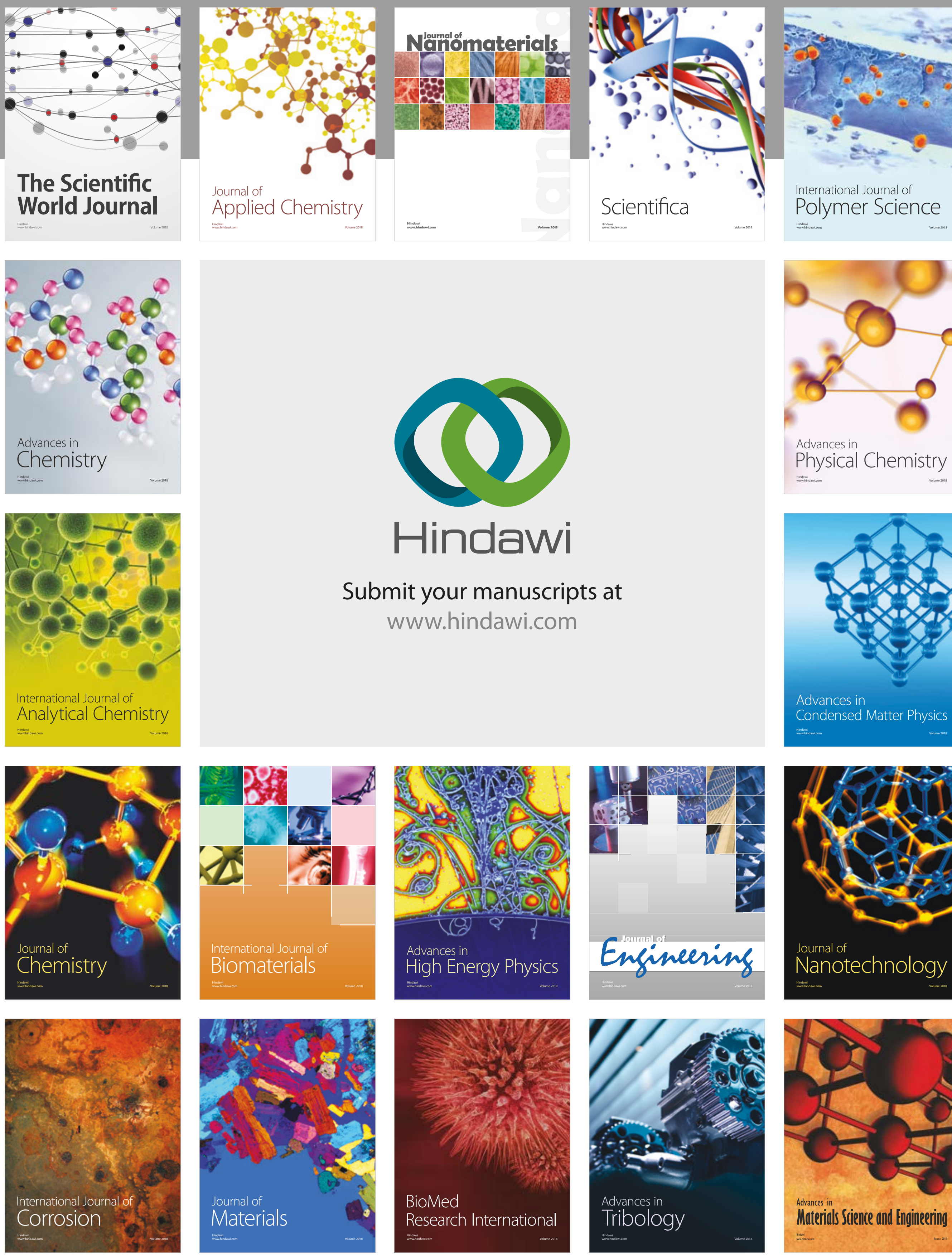
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