# Effect of Cold Working on the Residual Stress around the Notch front of Stress Corrosion Cracking

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**Abstract.** Failures show that the austenitic stainless steel (SS) pipes with produced high weld residual stresses are more susceptible to stress corrosion cracking in the simulated high temperature water environments of pressurized water reactor. To understand the effect of cold working on the residual stress and strain of stress corrosion cracking in 304SS, the stress-strain field near the crack front of 304SS under different degree of cold working was simulated by ABAQUS. Results show that the higher tensile residual stress and the larger compressive residual stress simultaneously occurs in the lower cold working material, and cold working has greater effect on the residual stress than on the residual strain. The residual compressive stress and residual compressive strain both decrease rapidly in a small range around the notch fronts and tend to be consistent in a more larger distance. But cold working has little effect on the residual strain.

## 1. Introduction

Stress corrosion cracking (SCC) is a failure mechanism that is caused by environment, susceptible material and tensile stress of nuclear power structural materials under high temperature and high pressure water environments [1]. Failures show that the austenitic stainless steel (SS) pipes with produced high weld residual stresses is more susceptible to SCC in the simulated high temperature water environments of pressurized water reactor [2-4]. Generally, weld residual stresses (RS) in pipe joints are up to or even over the material yield stresses at service temperature. Tensile residual stress is one of dominant factors resulting in SCC of these joints [5]. RS may have a great contribution to the total stress field when pipe surface SCC in nuclear power plants is assessed. Therefore, before evaluating SCC growth at flaws in actual pipe joints of PWR plants, accurate RS distribution needs to be performed.

During the manufacturing and assembly process under the nuclear power equipment, a certain degree of cold working (CW) will occur [6]. Many research shows that cold working has a great effect on the local mechanical field around the crack tip [7-8]. The amount of CW will also affect the state of RS field and the SCC growth rate of the nuclear power equipment [9]. Therefore, it is very important to obtain the effect of cold working on local residual stress and strain around the crack tip for quantitative prediction nuclear structure life.

Pressure was introduced in a pre-crack CT specimen to produce RS around the crack front. Finite element models of 304SS CT specimens are established under different degree of CW. The mechanical properties of crack tip region were simulated in the presence of residual stress. The effects of cold working on local residual stress and strain around the crack front are also investigated.

## 2. Finite element modelling

### 2.1. Specimen model

A notched compact tension (CT) specimen (specimen width *W*=20 mm) was performed in the finite element analysis, and its geometry and dimensions are shown in figure 1. To eliminate the stress singularity generated at the crack tip, the crack notch radius was taken as 0.25 mm in the finite element simulation. To avoid the contact between upper and lower surfaces in the process of residual stress induced by pressure, a groove (width is 2.5 mm and length is 11 mm) was machined at the front of the specimen gap [10].
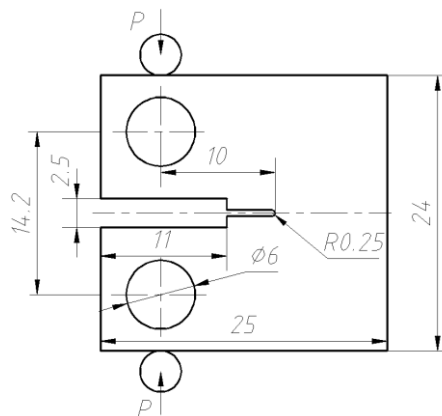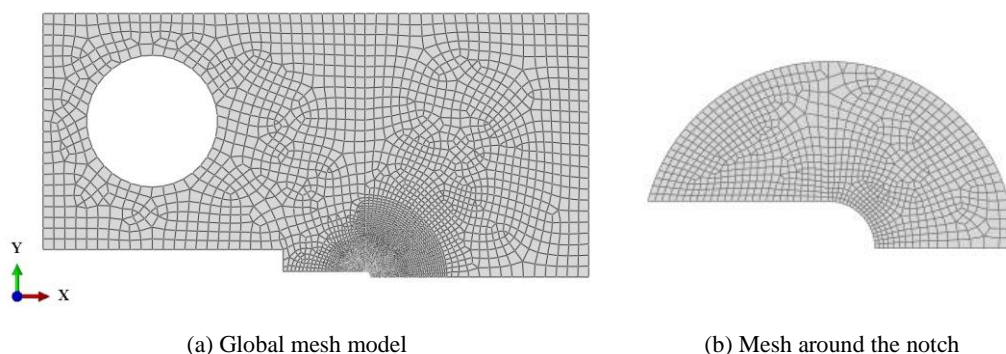


**Figure 1**. Geometry and dimensions of CT specimen (*W*=20 mm)

Due to symmetry, only one half of the specimen geometry was modeled, and the typical finite element model and meshes are illustrated in figure 2(a), which contains 20156 8-node biquadratic plane strain elements. To obtain more detailed and accurate stress-strain field, the mesh around notch front was refined as shown in figure 2(b).



(a) Global mesh model                                  (b) Mesh around the notch

**Figure 2**. Finite element mesh model of CT specimen

### 2.2. Material model

The specimen adopted in this study is 304SS and its chemical chemical composition includes C-0.043%, Si-0.4%, Mn-1.18%, P-0.033%, S-0.002%, Ni-8.04%, Cr-18.115%, N -0.046% etc. The geometry and dimensions of the specimen are shown in figure 3 below. Tensile experiment was carried out in fatigue stretcher machine under different cold working degrees, engineering stress and

strain curve was derived and converted to true stress-strain curves. The material true mechanical curves was shown in figure 4 under the degree of cold working is 0%, 10% and 20%, respectively.
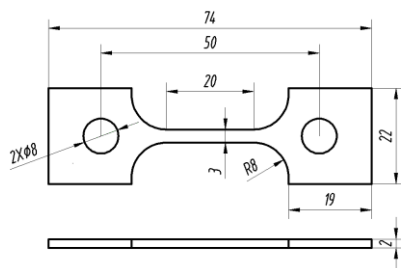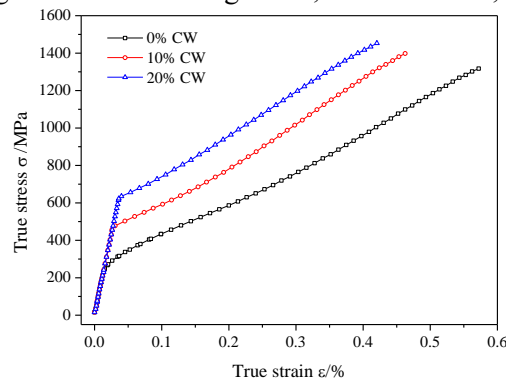
**Figure 3**. Plate tensile specimen

**Figure 4**. True stress-strain curves under different CW

### 2.3. Loading and boundary conditions

Two analysis steps were set in this simulation. The first one is the loading process, and displacement loading is applied to the reference point of rigid body and its value was set as 0.5 mm in the compressive direction. The other is the process of unloading, which sets the displacement load free. To eliminate the rigid body displacement during the period of loading and unloading, two points in the right side of the CT specimen was constrained in rotation and movement of X direction.

## 3. Results and Discussion

### 3.1. Effects of CW on residual stress and strain around the notch fronts

The residual stress distribution around the notch fronts under different degree of CW is shown in figure 5. The tensile residual stress decreases with the increasing CW. And the tensile residual stress mainly distributes in the near notch region, and gradually becomes compressive residual stress with the increasing distance away from the notch front. Cold working has great effect on the compressive residual stress.
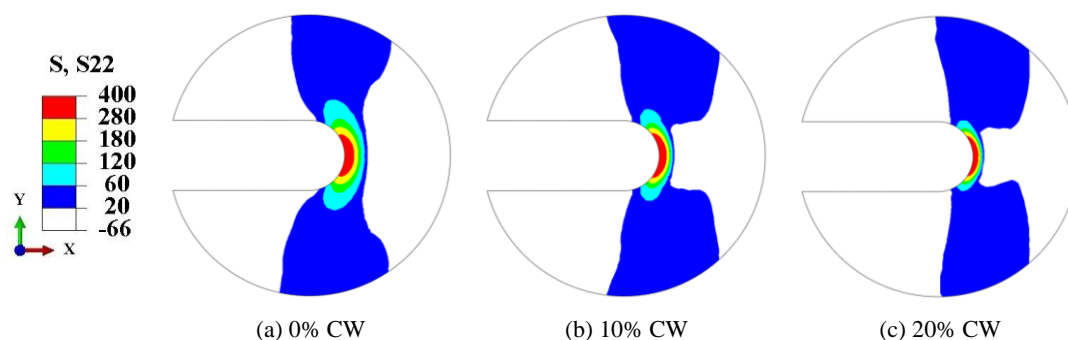
**Figure 5** Residual stress around the notch fronts under different degree of CW (MPa)

The residual strain distribution around the notch fronts under different degree of CW is shown in figure 6. The residual tensile strain is mainly distributed in the direction of perpendicular to the notch and the compressive strain is mainly distributed in the front of the notch. The tensile residual strain increases with the increasing CW. Moreover, CW has little effect on the compressive residual strain.
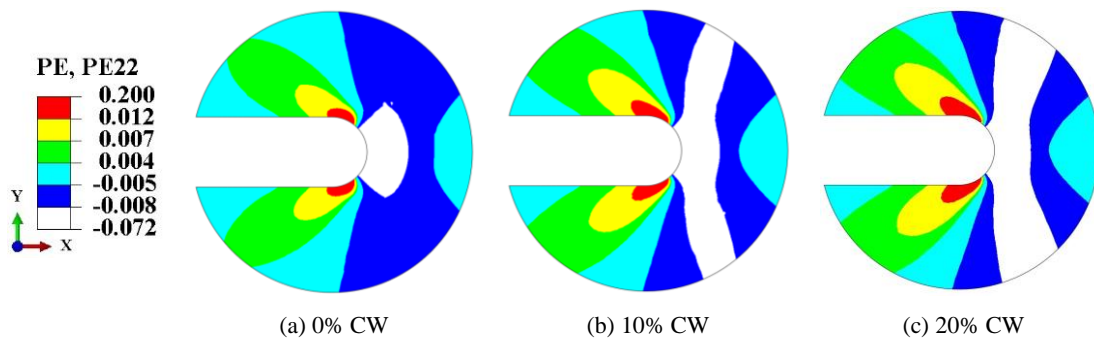
(a) 0% CW                     (b) 10% CW                     (c) 20% CW

**Figure 6** Tensile residual strain around the notch fronts under different degree of CW

*3.2. Residual stress around the notch fronts under the influence of CW*

The tensile residual stress distribution in front of notch front under different degree of CW is shown in figure 7. The residual stress decreases rapidly from tensile to compressive in a small range of 0.1 mm in the notch zone and tends to be consistent in a more larger distance from notch front. The higher tensile residual stress and the larger compressive residual stress also occurs in the lower cold working material.
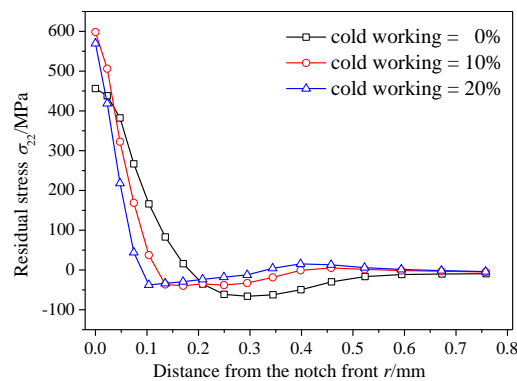


**Figure 7** Residual stress around the notch fronts (MPa)

*3.3. Residual strain around the notch fronts under the influence of CW*

The tensile residual strain distributions around notch fronts under different degree of CW is shown in figure 8. The compressive residual strain decreases rapidly in a small range around the notch fronts and tends to be consistent in a more larger distance. The cold working has little effect on the residual strain.
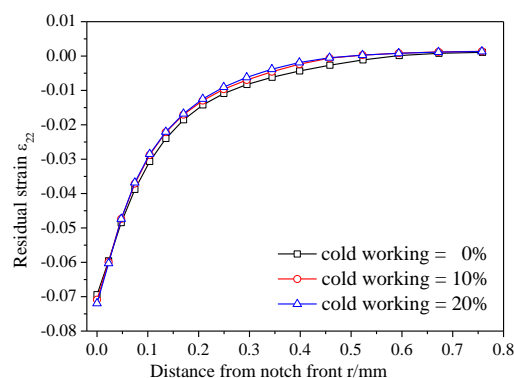


**Figure 8** Residual strain  around the notch fronts

## 4. Conclusions

(1) Near the notch region, residual stress gradually becomes compressive stress with the increasing distance from the notch front. Residual stress decreases rapidly from tensile to compressive in a small range around the notch fronts, and tends to be consistent in a more larger distance from notch front. The higher tensile residual stress and the larger compressive residual stress also occurs in the lower cold working material. CW has great effect on the residual stress.

(2) Tensile residual strain is mainly distributed in the direction of perpendicular to the notch and the residual compressive strain is mainly distributed in the front of the notch. The residual compressive strain decreases rapidly in a small range around the notch fronts, and tends to be consistent in a more larger distance. CW has little effect on the residual strain.

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