Investigation of quenching stress of 42CrMo treated by alternately timed quenching process

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ABSTRACT
Alternately timed quenching (ATQ) technology includes ATQ process and equipment. ATQ process essentially executes multicycle quenching-partitioning-tempering (MQ-P-T) process by alternative water -quenching and air cooling. Engineering applications indicate that ATQ process not only can replace oil or aqueous polymer solution quenching, but also reach even be superior to the mechanical properties of workpieces quenched by oil or aqueous polymer solution. Since direct water-quenching usually causes the cracking of workpieces, polluting oil quenching or aqueous polymer solution quenching is still used in modern industry. The combination of water-quenching and air-cooling can effectively avoid the cracking of workpieces, but direct water-quenching (DQ) process very easily causes cracking, and this issue puzzles us for a long time. In this work, 42CrMo cylinder with 60 mm in diameter respectively treated by ATQ process and DQ process for comparison is taken an example, and the quenching stress of 42CrMo cylinder is investigated by the finite element simulation (FES) and X-ray diffraction (XRD) measurement, respectively. The results reveals the origin of avoiding cracking of workpieces for ATQ process, that is, ATQ process markedly lowers the quenching tensile stress and raises its uniform distribution compared with DQ process.

1. Introduction

Water-quenching was used to improve the mechanical properties of steels two thousand years ago [1]. However, since water-quenching usually causes the cracking of workpieces, oil quenching or aqueous polymer solution quenching is still used in modern industry. Oil quenching or aqueous polymer solution quenching will lead to severe air-pollution and production safety. Fifteen years ago, we developed water-air alternative timed quenching (ATQ) technology based on traditional gap quenching technology [2]. ATQ technology contains both ATQ process and ATQ equipment. Based on the finite element simulations of temperature field, transformation field and stress field, the time of both water-quenching and air-cooling can be properly designed and precisely controlled so that ATQ technology can effectively avoid the cracking of alloying workpieces and reach even be superior to the mechanical properties of workpieces quenched by oil or aqueous polymer solution, such as 42CrMo4 marine crankshaft and a wind-electric spindle. The cooling rate of water is higher than that of oil or aqueous polymer solution, while the cooling rate of air is lower than that of oil or aqueous polymer solution, as a result, the proper ratio of water-quenching time and air-cooling time can reach the cooling rate of oil or aqueous polymer solution [3]. A new quenching-partitioning-tempering (Q-P-T) process was proposed by Hsu in 2007 [4], which absorbs the core idea of quenching and partitioning (Q&P) process proposed by Speer et al. in 2003 [5], that is, (i) a fast quenching to a temperature $T_q$ which is between the start temperature ($M_s$) and finish temperature ($M_f$) of the martensitic transformation, and $T_q$ is usually much higher than room temperature; (ii) a subsequent partitioning at or above $T_q$ to accomplish the partitioning (diffusion) of carbon from supersaturated martensite into retained austenite so as to keep carbon-enriched retained austenite stable during subsequent cooling to room temperature. Since Q-P-T steels contain over 1.0 Si wt% and Si effectively stimulates the partitioning of carbon from martensitic matrix to retained austenite so that Q-P-T steels have much more retained austenite than the same composition steels treated by traditional quenching and tempering (Q&T) ($T_q$ is room temperature) accompanying with much better ductility of low carbon, medium carbon and high carbon Q-P-T martensitic steels than that of Q&T martensitic steels [6–8]. Because of the limitation of the Q-P-T process in application of hot-rolled plates, we further proposed a multi-cycle Q-P-T (MQ-P-T) process [9,10]. Obviously, ATQ process

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essentially executes MQ-P-T process by alternative water and air cooling, that is, water cooling executes quenching between $M_s$ and $M_f$ and air cooling does the partitioning of carbon from martensite to retained austenite and the precipitation of carbides from martensitic matrix during self-tempering. Hsu proposed quenching-partitioning-tempering (Q-P-T) process in 2007 [4], which absorbs the core idea of quenching and partitioning (Q&P) process proposed by Speer et al. in 2003 [5], that is, (i) a fast quenching to a temperature $T_q$ which is between the start temperature ($M_s$) and finish temperature ($M_f$) of the martensitic transformation, and $T_q$ is usually much higher than room temperature; (ii) a subsequent partitioning at or above $T_q$ to accomplish the partitioning (diffusion) of carbon from supersaturated martensite into retained austenite so as to keep carbon-enriched retained austenite stable during subsequent cooling to room temperature. so that the combination of alternative water-quenching and air-cooling effectively can avoid cracking tendency and obtain good mechanical properties.

In other words, MQ-P-T process is equivalent to ATQ process. It is worth to pointing out that high quenching temperature $T_q$ in Q-P-T or Q&P process than that in Q&T process is to obtain more retained austenite if the amount of Si in steels is above 1.0 wt%, otherwise, the retained austenite fraction in Q-P-T steels almost has the same as Q&T steels. Even though, we found other two advantages of high quenching temperature [2]: effectively reduce quenching stress and refine martensitic matrix. Therefore, the mechanism that the ATQ process improves mechanical properties can be revealed by the comparison of MQ-P-T process with Q&T process. However, why and how ATQ process can effectively avoid the cracking of workpieces has been not yet revealed.

In this work, 42CrMo cylinders with 60 mm in diameter were treated by ATQ process and DQ process respectively for comparison is taken an example, and the quenching stress of 42CrMo cylinder is investigated by the finite element simulation (FES) and X-ray diffraction (XRD) measurement, respectively. The origin of avoiding cracking of workpieces for ATQ process will be expected to reveal.

2. Experimental procedures

The composition of the studied steel 42CrMo was chemically analyzed as Fe–0.39C–0.28Si–0.59Mn–0.10Cr–0.17Mo–0.022Ni. The phase transformation start temperature from austenite to bainite or martensite were calculated by Jmatpro as 558°C or 339°C, respectively. The tested cylinders were 60 mm in diameter and 240 mm in length. Before quenching test, the cylinders were annealed at 850°C for 120 min. During the quenching process, the cylinders were first heated in pit type furnace at 850°C for 90 min to ensure that the specimens were completely austenitized. After heating, one sample was quenched by DQ process (precooled in air for 30 s and then immersed into water for 150 s), and another sample was quenched by ATQ process (precooled in air for 30 s, and then immersed in water and air alternately: 20 s in water, plus 5 s in air, plus 10 s in water, plus 10 s in air, plus 5 s in water and then air cooled until the temperature drops to room temperature (32°C). The above precooling is to reduce the thermal capacity and accelerate the cooling rate of quenching stage in engineering [2]. During ATQ process, the decrease of immersion time in water from 20 s to 5 s is to lower the phase transformation stress [11].

The quenched cylinders were cross-sectioned, mechanically polished and then etched first with 2% nital (2 ml of HNO$_3$ and 98 ml of ethyl alcohol) for 10 s and subsequently with Vilella (0.5 ml of picric acid, 2.5 ml of HCl, and 50 ml of C$_2$H$_5$OH) for 5 s [12]. The etched samples were used for optical microscopy (OM; Imager A1 m) and field-emission scanning electron microscopy (FE-SEM; JEOl, JSM7600F). Specimen for transmission electron microscopy (TEM) was prepared by mechanically polishing and the electropolishing in a twin-jet polisher using 6% perchloric acid and 94% ethanol at 253K-243 K (~20°C~30°C). TEM was performed in a JOEL-2100F microscope operated at 200 kV.

The residual stress of the quenched cylinders was measured by X-ray diffraction (iXRD combo, PROTO Company). The $\sin^2\psi$ method was used in this study [13]. If the stress state is biaxial, a straight line should be experimentally obtained. The stress in the $\varphi$ direction, $\sigma_\varphi$, is calculated from the slope of the straight line:

$$\sigma_\varphi = \frac{\frac{\frac{\partial I_{200}}{\partial \psi}}{2\sin^2\psi}}{\frac{\frac{\partial I_{211}}{\partial \psi}}{\frac{1}{2} \sin^2\psi}},$$

where $\varphi$ is the angle between a measured direction in the plane of the specimen and the projection in that plane of the normal to the diffracting lattice planes, and $\varphi = 0$ in this work for Omega geometry; $\psi$ is the angle between the normal of the specimen and the normal of the diffracting lattice planes; $I_{200}$ is the strain in the direction defined by the angles $\varphi$ and $\psi$ for the family of lattice planes $\{hkl\}$; $\frac{\partial I_{211}}{\partial \psi}$ is the X-ray elasticity constants for the family of lattice planes $\{hkl\}$; Cr radiation ($\lambda = 0.2291$ nm) was employed with a spot diameter of 2 mm. The values of $\psi$ were ±0°, ±12°, ±24°, ±30°, ±37° and ±43°, respectively; the reference crystallographic planes was (211) of bcc-phase, and the corresponding elasticity constant $\frac{1}{2} \frac{\partial I_{211}}{\partial \psi}$ was 5.92 × 10$^{-6}$ MPa$^{-1}$ for 42CrMo. In order to measure the residual stress distribution along radius, the remover of the outer layer was required. The cylinder
was first lathed and then etched by a nitric acid aqueous solution (150 ml HNO₃, 50 ml H₂O₂, 20 g H₂C₂O₄) for at least 0.5 mm. The remover of the outer layer may cause the redistribution of the stress, and thus the measured values of residual stress after removal of material should be corrected in order to obtain the true stress distribution that existed before the layers were removed. The correction formulations proposed by Moore and Evans [14] were used in this study:

\[
\sigma_i(r) = \sigma_m(r) - \int_r^R \sigma_m(\xi) \cdot \frac{d\xi}{\xi},
\]

\[
\sigma_z(r) = \sigma_m(r) - 2 \int_r^R \sigma_m(\xi) \cdot \frac{d\xi}{\xi},
\]

where \(\sigma_i(r)\) and \(\sigma_z(r)\) are tangential stress and axial stress corrected at the radius of \(r\) respectively; \(\sigma_m(r)\) and \(\sigma_m(R)\) are the measured tangential stress and axial stress at the radius of \(r\); \(R\) is the initial radius of the sample.

### 3. Simulation details

The coupling between temperature, phase transformations and mechanical behavior was presented by Leblond et al. [15]. Among those interactions, the influence of the mechanical behavior on temperatures through deformation energy was ignored because this effect is very small (about 2°C); [15] the effect of stress on phase transformations was also not considered in this work due to the lacking of experimental data and reliable models. So the entire coupling can be simplified into a sequentially coupled thermal-stress analysis.

By introducing the phase transformation latent heat, a governing equation for the calculation of temperature was expressed as [16]

\[
\rho C_p(\varphi_i, T) \tilde{T} = \nabla (k(\varphi_i, T) \cdot \nabla T) + \tilde{Q},
\]

where \(\rho\) is the density and taken as 7850 kg/m³; \(C_p\) and \(k\) is specific heat and thermal conductivity of the phase mixture, respectively; \(T\) is the temperature, and \(\tilde{T}\) is the time derivative of the temperature; \(\nabla\) denotes the gradient operator; \(\tilde{Q}\) is the transformation latent heat rate:

\[
\tilde{Q} = \sum_{i=2}^{5} \Delta H_i \dot{\varphi}_i,
\]

where \(\Delta H_i\) represents the enthalpy of the phase transformation; \(\dot{\varphi}_i\) is the transformation rate of \(i\) phase; \(i\) represents austenite, ferrite, pearlite, bainite and martensite when \(i = 1, 2, 3, 4\) and 5, respectively.

The initial temperature of the analysis was set to a uniform value of 1123 K (850°C), being the austenitizing temperature of 42CrMo. Boundary (film) conditions were set at the surfaces of the cylinders contacting with the water:

\[
-k(\varphi_i, T) \nabla T = h(T)(T_s - T_w),
\]

where \(h(T)\) is the heat transfer coefficient (HTC) of water; \(T_s\) and \(T_w\) are the temperatures of cylinder’s surface and water, respectively.

The kinetic of austenite-martensite transformation in steels is dependent only on temperature, Eq. [6] describes the volume fraction of martensite, \(\varphi_M\) as a function of temperature: [17,18]

\[
\varphi_M = 1 - \exp\{-\alpha_M(M_s - T_0)\},
\]

where \(\alpha_M\) is a rate parameter; \(T_0\) is the lowest temperature reached during quenching; Koistinen and Marburger [17] argued that \(\alpha_M = 0.011 K^{-1}\) which is independent of composition, while Bohemen and Sietsma [18] concluded that \(\alpha_M\) is composition dependent for the low alloyed steels with carbon contents in the range between 0.3 and 1.1 wt%. The rate parameter can be described by a simple linear equation:

\[
\alpha_M = 0.0224 - 0.0107x_C - 0.0007x_Mn
\]

\ [-0.00005x_Ni - 0.00012x_Cr - 0.0001x_Mo].

Equations (6) and (7) were employed in this study.

As for the ferrite, pearlite and bainite, the kinetic equation at constant temperature proposed by Austin and Ricket [19] was described as:

\[
\frac{\varphi_i}{1 - \varphi_i} = \left(\frac{t}{\tau_i(T)}\right)^n(T),
\]

where \(\tau_i(T)\) as a function of temperature is the time need to transform 50% of \(i\) phase; \(n(T)\) is a parameter weakly depending on temperature. But during continuous cooling of the quenching, phase transformations mentioned above occur neither at a constant temperature nor at a constant cooling rate condition, which makes the calculation of phase transformation during the quenching process rather complex. The common solution for this problem is combining isothermal equation with Scheil’s additive rule [20].

During the quenching process, the total strain increment was divided into five parts:

\[
\Delta e_{ij} = \Delta e_{ij}^{el} + \Delta e_{ij}^{pl} + \Delta e_{ij}^{th} + \Delta e_{ij}^{tr} + \Delta e_{ij}^{tp},
\]

where \(\Delta e_{ij}^{el}\), \(\Delta e_{ij}^{pl}\), \(\Delta e_{ij}^{th}\), \(\Delta e_{ij}^{tr}\) and \(\Delta e_{ij}^{tp}\) are the strain increment of elastic, plastic, thermal, phase transformation and transformation plasticity, respectively. Assume that if the materials are isotropic, the thermal strain and transformation strain increment are also isotropic and were calculated by the following equations,
respectively:

\[
\Delta \varepsilon_{ij}^{s} = \delta_{ij} \sum_{l=1}^{5} \varphi_{l}(\varepsilon_{l}(T + \Delta T) - \varepsilon_{l}(T))
\]

\[
\Delta \varepsilon_{ij}^{s} = \delta_{ij} \sum_{l=2}^{5} \Delta \varphi_{l}(\varepsilon_{l}(T + \Delta T) - \varepsilon_{l}(T + \Delta T)),
\]

where \(\varepsilon_{i}\) is the strain of the \(i\)th phase and were calculated based on experimental thermal expansion curves. \(\delta_{ij}\) is the Kronecker delta function. When phase transformations occur under stresses, an anomalous plastic strain is added to the stress. The yield strength of the phase mixture, which was calculated based on a non-linear (parabolic approximation) mixture rule [24] since the relatively large overestimation of the stress is exhibited by using the simple linear rule. The plastic flow rule was expressed as [25]

\[
\Delta \varepsilon_{ij}^{pl} = \frac{3}{2} \frac{2G}{l} \varepsilon_{ij}^{pl} - \frac{3}{2} \frac{2G}{l} \varepsilon_{ij}^{pl} - \frac{3}{2} \frac{2G}{l} \varepsilon_{ij}^{pl} = \frac{3}{2} \frac{2G}{l} \varepsilon_{ij}^{pl} - \frac{3}{2} \frac{2G}{l} \varepsilon_{ij}^{pl}.
\]

\[
\Delta \alpha_{ij}^{pr} = \Delta \varepsilon_{ij}^{pr} + \frac{1}{3} \Delta \alpha_{kk} \delta_{ij}
\]

\[
= \left[ \frac{2G}{l} \Delta \varepsilon_{ij}^{pr} + \left( B - \frac{2G}{3l} \right) \Delta \varepsilon_{ij}^{pr} \delta_{ij} \right] + \left[ \frac{2G}{l} \varepsilon_{ij}^{pl} + \left( \Delta B - \frac{2G}{3l} \right) \varepsilon_{ij}^{pl} \delta_{ij} \right] + \left( \Delta B - \frac{2G}{3l} \right) \varepsilon_{ij}^{pl} \delta_{ij}.
\]

where \(f\) is the yield function written as [25]

\[
f(\varepsilon_{ij}^{pr}, \varepsilon_{eq}^{pl}) = \frac{3}{2} \varepsilon_{ij}^{pr} - \alpha_{ij}^{0} (\varepsilon_{ij}^{pl} - \alpha_{ij}^{0}) - \alpha_{ij}^{pl} \varepsilon_{eq}^{pl},
\]

where \(\alpha_{ij}\) is the deviator of the backstress tensor; \(\alpha_{ij}\) is the yield strength of the phase mixture, which was calculated based on a non-linear (parabolic approximation) mixture rule [24] since the relatively large overestimation of the stress is exhibited by using the simple linear rule. The plastic flow rule was expressed as [25]

\[
\Delta \alpha_{ij}^{pr} = \frac{3}{2} \varepsilon_{ij}^{pr} - \alpha_{ij}^{0} (\varepsilon_{ij}^{pl} - \alpha_{ij}^{0}) - \alpha_{ij}^{pl} \varepsilon_{eq}^{pl}
\]

\[
\Delta \alpha_{ij}^{pr} = \frac{2}{3} H \Delta \varepsilon_{ij}^{pl}
\]

where \(H\) is the plastic-hardening modulus.

The commercial finite element software, Abaqus/Standard, was used to solve the heat transfer analysis and stress/displacement analysis. Phase transformation and the related transformation latent heat were implemented in user subroutine UMATHT. The 4-node linear diffusive heat transfer element DCAX4 was used for heat analysis and CAX4 for stress/displacement analysis because of axial symmetry in geometry and loads for the quenched cylinders. The models of transformation plasticity mentioned above were added in the user subroutine UMAT. Heat transfer coefficient of water, thermal and mechanical properties of each phase can be found in Reference [26,27]. The 60 mm diameter cylinder was meshed into 6364 nodes and 6174 elements, in which the mesh sizes close to the surface were refined.

4. Results

4.1. Calculation of cooling curves

Figure 1 shows a comparison between the calculated cooling curves for the 42CrMo cylinders at the core, 1/2 radius, 5 mm distance from the surface and surface during quenching by ATQ and DQ, respectively. At the precooling stage in air during the initial 30 s, the temperature decreased slowly because of a low heat transfer coefficient (HTC) of air, but dropped dramatically after immersion in water due to the high HTC of water. It can been seen from Figure 1 that when the temperature was above 450°C, there was no difference of cooling rate at different locations between ATQ and DQ, and thus no proeutectoid ferrite or pearlite transformations occur, which is consistent with the result of microstructural characterization, as shown in Figure 2. When the temperature dropped below 450°C, the cooling rate of ATQ was slower than that of DQ, being favorable for the decrease of phase transformation stress due to the decrease of driving force of phase transformation. After the first water immersion, the surface temperature decreased to 150°C, and almost 95% austenite transforms to martensite at the surface. When the cylinder was shift to air, due to the low HTC of air, the temperature of surface increased to 310°C which is caused by the heat conduction from the core. The increase of temperature at surface not only can enhance the toughness of steel by self-tempering effect, but also can decrease the temperature gradient of the cylinder, and this is beneficial for the preventing the formation of crack during quenching.

4.2. Phase distribution

The OM and SEM photographs in Figure 2 show the microstructures of the 42CrMo steel at the location of 5 mm from surface, 1/2 radius and core after ATQ treatment. At the location of 5 mm from surface, the microstructure is self-tempered martensite that is caused by
the rise of temperature at the air cooling stage. Figure 3 shows TEM images of martensitic matrix, bainite and retained austenite at core of 42CrMo cylinder. It is worth to pointing out that since 42CrMo steel only has 0.28 Si wt%, much less than 1.0wt%, since the little Si cannot effectively stimulate the partitioning of carbon from martensitic matrix to retained austenite, the retained austenite fraction is very small (less

Figure 1. Comparison of the calculated temperature history for 42CrMo cylinders at the core, 1/2 radius, 5 mm below surface, and surface during quenching by ATQ and DQ.

Figure 2. OM (a, c and e) SEM (b, d and f) micrographs of 42CrMo cylinder after ATQ process: 5 mm from surface (a and b); 1/2 radius (c and d); core (e and f).
than 3%) so that it cannot be found in X-ray diffraction spectrum. Figure 4 displays the TEM image of tempered martensite at this location below 350°C and the distribution of carbides with the average size less than 200 nm precipitated from martensitic matrix. As the location shift from surface to the core of the cylinder, due to the decrease of cooling rate, as shown in Figure 1, the amount of tempered martensite decreases accompanying with the increase of bainite amount. At the core, the amount of bainite exceeds 60%.

### 4.3. Residual stress distribution

Figure 5 shows the measured and simulated axial and tangential residual stress distributions of 60 mm diameter 42CrMo cylinders after treated by ATQ and DQ, respectively. The simulated residual stress distributions are consistent with the measured ones, which indicate that the FES in this study can predict the residual stress trends of the ATQ process. The residual stress distributions of the cylinders treated by the two processes have some similarities: (1) the axial and tangential residual stresses are compressive stress at the surface and tensile stress at the core; (2) the axial tensile stress at the core is higher than that of tangential, while the tangential compressive stress at the surface is higher than that of axial; (3) at the radius of 22 mm, the residual stress is almost zero. But there are also some differences of the residual stress distributions between ATQ and DQ processes: (1) there is a tensile stress peak at subsurface (about 5 mm below surface) for ATQ, which is less than maximum tensile stress at the core for DQ; (2) the gap of maximum tensile stress and compressive residual stress after ATQ treatment is lower than that treated by DQ process, implying the stress distribution along the radius of cylinder for ATQ process is relatively uniform comparing with DQ process. Therefore, it is
reasonably believed that the low tensile stress and uniform stress distribution are the origins of avoiding the cracking of workpieces for ATQ process.

5. Discussions

5.1. Separation simulation of thermal stress and phase transformation stress

As is known, non-uniform cooling rate and phase transformation is the cause of internal stress generation for the quenched workpieces. The quenching stress is result of the interaction (overlapping) between thermal stress and phase transformation stress. Separation of the two kinds of stress distributions is an effective method for analyzing the quenching stress. These two stresses cannot be separately obtained by experimental measurement, but can be separately calculated out by omitting thermal strain for phase transformation stress or omitting phase transformation strain for thermal stress in Equation (9). Figure 6 shows the separated thermal and phase transformation stress distributions of 60 mm diameter 42CrMo cylinders after treated by ATQ process and DQ process, respectively. It can be found that the thermal stress results in tensile stress at the core and compressive one at the surface; while the phase transformation stress causes the maximum tensile stress at surface and the maximum compressive stress at the core. This phenomenon is consistence with some references [27,28]. It is evident that the compressive residual stress at surface and tensile residual stress at core shown in Figure 5 was the result of the thermal stress for both ATQ process and DQ process. By comparing with DQ and ATQ, as shown in Figure 6, it can be seen that ATQ process dramatically decreases the gradient of thermal stress. This phenomenon can be explained by the temperature difference between the core and surface. During the air cooling stage for ATQ process, the temperature difference between the core and surface was reduced as shown in Figure 1, correspondingly, thermal stress exhibits lower tensile stress and uniformly distribution from the core to 10 mm from surface comparing with DQ process. Meanwhile, the small temperature difference between the core and surface for ATQ process reduces the difference of driving force of phase transformation, which lead to the uniform distribution of phase transformation stress comparing with DQ process. Although the compressive stress from the surface to 25 mm radius for ATQ process is less than that for DQ process, the difference between thermal stress and phase transformation stress evidently decrease, which leads to the uniform distribution of quenching stress comparing with DQ process, as shown in Figure 5. Therefore, it is reasonably concluded that low tensile stress and its uniform distribution are the origins of avoiding the cracking of workpieces for ATQ process. Meanwhile, we give a safe conclusion: to control thermal stress is to control phase transformation stress, in turn control quenching stress, in other words, to control heat history of cooling by design of proper ratio of water-quenching time and

Figure 5. Axial (a) and tangential (b) residual stress distributions of 60 mm diameter 42CrMo cylinder after treated by ATQ and DQ.

Figure 6. Simulated thermal and phase transformation stress distributions of 42CrMo cylinder with 60 mm in diameter treated by ATQ and DQ: (a) axial stress, (b) tangential stress.
air-cooling time in ATQ process is to control the quenching stress so that proper ATQ process can effectively avoid the cracking of workpieces during quenching.

5.2. Evolution of transient stress during ATQ process

In many cases, the cracking happened during the quenching process rather than after the process, and this type of cracking is caused by transient stress rather than residual stress. Unfortunately, up to now it is impossible to measure the transient stress by experiment. So the simulation of transient stress is crucial when design quenching process. Figure 7 shows the calculated tangential stress evolution at three midsection points (surface, 1/2 radius, and core) of 60 mm diameter cylinder when performing ATQ process. The stress is almost zero during the precooling stage due to the slow cooling rate. After precooling, the cylinder was immersed into water for 20 s, and the stress at surface was tensile at first because of cooling contraction at this location, but when the surface temperature dropped below the start temperature of martensitic transformation ($M_s$) due to the expansion of martensite formation, the tensile stress dramatically inverts to compress stress. In order to keep balance, the stress in the core is compressive at first, and then transfers to tensile. During the first and second air cooling stages, the surface temperature increases, as shown in Figure 1, and the thermal expansion at surface makes the compressive stress form two valley bottoms, and at the core and 1/2 radius the increase of the tensile stress is to keep the balance of the compressive stress of two valley bottoms. In the second and third water cooling period, the cooling rate at the surface increases strongly again, but there is no martensitic or bainitic transformation at the surface, just cooling contraction generates and decreases the compressive stress at the surface, and correspondingly, the tensile stress at the core and 1/2 radius also lowers. After cooling 80 s, the temperature drops below 400°C, the cylinder is transferred to air-cooling until to room temperature. In this final air-cooling stage, the compressive stress at surface increases at first when the temperature increases, and then the compressive stress decreases to balance the decrease of tensile stress from the martensite formation at 1/2 radius and the core. Figure 6(b) shows the calculated tangential stress evolution at three midsection points (surface, 1/2 radius, and core) of 60 mm diameter cylinder when performing DQ process. Similar to ATQ process, the stress is almost zero during the precooling stage due to the slow cooling rate. After precooling, the cylinder was immersed into water for 150 s, and the stress at surface was tensile at first because of cooling contraction at this location, but when the surface temperature dropped below the start temperature of martensitic transformation ($M_s$) due to the compressive stress produced by expansion of martensite formation, the tensile stress dramatically inverts to compress stress. In order to keep balance, the stress in the core is compressive at first, and then transfers to tensile. After 50 s cooling, no martensitic occurs at the surface, and cooling contraction produces tensile stress accompanying with the decrease of the compressive stress at the surface, meanwhile, bainitic transformation and martensitic transformation successively at 1/2 radius and the core occur accompany with the generation of compressive stress. In order to balance the compressive stress at 1/2 radius and the core, the compressive stress further decreases. After 70 s cooling, with the reduction of phase transformation in volume fraction and the finish of phase transformation (see Figure 1), the compressive stress produced by phase transformations gradually decreases accompanying with the decrease of tensile stress at the surface for balance, that is, the compressive stress at the surface gradually increases. Comparing Figure 6(a) with 6(b), it can be found that every air cooling during ATQ process strongly enhances the compressive stress at the surface, but the tensile stress at 1/2 radius or the core is almost the same in the magnitude as DQ process. Since every air cooling effectively relaxes transformation stress, which leads to the distribution of lower tensile stress during ATQ process than DQ one (Figure 7).
6. Conclusions
In order to understand the origin of avoiding cracking of workpieces treated by ATQ process, which is equivalent to MQ-P-T process, two 60 mm diameter 42CrMo cylinders were selected for investigation: one was treated by ATQ, and the other was quenched by DQ process for comparison. The microstructures in 42CrMo steel under ATQ and DQ processes were characterized by OM, SEM and TEM. The residual stress distribution were measured by XRD and was compared with the stress distribution calculated by FES. The compared result demonstrates low tensile stress and its uniform distribution are the origins of avoiding the cracking of workpieces for ATQ process. The separated calculations of thermal stress and phase transformation stress revealed that the control of thermal stress is to dominate phase transformation stress, in turn control quenching stress, in other words, to control heat history of cooling by design of proper ratio of water-quenching time and air-cooling time in ATQ process is to control the quenching stress so that proper ATQ process can effectively avoid the cracking of workpieces during quenching.

Disclosure statement
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