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# Preliminary Study to Identify Criterion for Quench Crack Prevention by Computer Simulation

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**Abstract:** A criterion for preventing quench cracks has not been established although much research has been conducted in this field. A few predictions of cracking have been recently reported using simulated results of heat treatment processes. However, these results were insufficient to predict crack generation clearly because the mechanism relates not only to stress distributions in the parts but also to material characteristics. Systematic studies by the combination of experiment and simulation are therefore required to reliably identify a criterion for crack prevention by computer simulation. As a preliminary work before starting the full-scale research, a review of quench cracking research was conducted and existing test methods were classified. Several test results for cylindrical specimens were simulated for considering a cause of the crack generation. Lastly a tentative plan was made for the future research.

**Key words:** Quench Cracking, Heat Treatment Simulation

A CRITERION for preventing quench cracks has not been established although many investigations have been conducted for this purpose. Some studies on the quench cracking were reviewed in the texts [1, 2]. Some researchers have indicated that tensile stresses may contribute to quench crack generation. Recently heat treatment simulation [3, 4] has showed evidence of this contribution. However, these results were insufficient to predict crack generation clearly because the complex mechanism relates not only to stress distribution in the parts but also to material characteristics.

Systematic studies combining experiment and simulation are therefore required to explain the mechanism of crack generation and to provide a strict criterion of crack prevention by computer simulation. This full-scale research will take a long period of time because of many comparisons for different shaped specimens, steels, heat treatment conditions, etc. A preliminary work is therefore appropriate to identify the course of the full-scale research.

A review of research on quench cracking was conducted and existing test methods were classified in this work. Several experimental results from literature were simulated for considering the causes of crack generation. Lastly a tentative plan was made for future research.

## 1. Review of Research on Quench Cracking

The research on the quench cracking has been reviewed in various texts [1, 2]. However, additional searching of the literature may be necessary. Selected major research works on quench cracking have been identified and outlined in chronological order. The study by Scott [5] in 1925 will be introduced first, because this would be the first investigation of cracking by experimental and theoretical techniques.

Scott examined the influences of different diameters and quenchants on quench cracking using cylindrical tool steel specimens, 4 in. (102 mm) length. He reported that cracks occurred on oil-quenched specimens between 3/4 in. (19 mm) and 1.5 in. (38 mm) diameter, and on water quenched specimens between 1/4 in. (6.4 mm) and 1/2 in. (12.7 mm). Distributions of axial residual stress were measured by the Heyn method [6] and calculated by an analytical technique. From these results, Scott concluded that cracks in steel are due to tensile stresses produced on the surface.

Buhler and Scheil [7] noted quench cracking related to their stress measurement of the quenched Ni steel cylinder, 50 mm diameter and 350 mm length. A longitudinal crack was observed on the specimen that was cooled initially in a furnace until the temperature decreased to 360°C and then quenched in ice water. They measured the circumferential stress distribution by the Sachs method [8] and identified a tensile stress region below the surface of the specimen quenched under the same condition as the above but without cracking.

Nishikiori and Iwaki [9] reported experimental results of quench cracking on tungsten steel cylinders, 13 mm diameter and 100 mm long, in 1936. In the steel, containing 0.84% C, 0.3% Cr, 2.28% W and 0.28% V, cracks occurred after quenching in water and oil, except for the 10% brine quenching. Tests using tungsten steel specimens with different chemical compositions showed that the quenching by oil and brine affects crack generation depending on the steel alloy.

Udy and Barnett [10] performed quench cracking experiments using cylinders, 1 in. (25.4 mm) diameter and 2 in. (50.8 mm) length for testing 120 steels in 1947. Notches, 1/16 in. (1.6 mm) wide, were sawed on both end-faces of a cylinder. The depth of notch varied from 1/8 in. (3.2 mm) to 7/8 in. (22.2 mm), in increments 1/8 in. (3.2 mm). The quench cracking index, *I'*=8-*n*, was proposed, where *n* denotes the minimum notch depth, in 1/8 in. unit, of the specimen to generate cracks due to flowing water quenching. The tendency was found out that steels with lower $M_s$ have higher crack susceptibility.

Wells et al [11] reported quench cracking tests using notched hollow disks in 1950. The steel specimens were approximately the same as 4335 steel. The dimension was 6.5 in. (165 mm) outside diameter, 2.75 in. (70 mm) inside diameter and 0.5 in. (13 mm) thick. The notch located close to the inner curved surface of the disk and its depth varied from 1/16 in. (1.6 mm) to 8/16 in. (12.7 mm) in increments 1/16 in. (1.6 mm). The measured minimum notch depth to crack by water spray quenching in 1/16 in. unit was specified as the "crack susceptibility index". Using the same experimental equipment and specimens as in the research by Wells et al., Spretnak and Busby [12] investigated the effect of the pre-bore quench to quench crack generation. The bore lead times of 10 to 20 s suppressed to generate cracks at both the inside and outer surface.

Chapman and Jominy [13] devised the disk specimen with an eccentric hole to evaluate the crack susceptibility of steels in oil or salt bath quenching. V-notches were provided on both the inside and outer surface at the thinnest section of the hole for easy generation of cracks. From the results of their tests, the effects of the austenitizing temperature, $M_s$, the amount of carbon and the ideal critical diameter were reported.

Isomura and Sato [14] quenched tool steel specimens, 18 mm diameter and 100 mm long, by water, and reported that the higher generation rate of quench cracking was exhibited in steels with higher austenitizing temperature and carbon content in 1961. It was reported that quenching cracks occurred on bearing steel cylinders, 18 mm diameter, with water quenching after 1 hr heating at 1000°C, while they were not found in oil quenching after 1 hr heating at 1100°C on the same specimens. In addition, although cracks on the same bearing steel specimens were not observed in water quenching after 1hr heating at 900°C, they occurred by water quenching after oil quenching for 5 to 20 s.

Isomura and Sato [14] considered the origin of quench cracks to be the maximum point of tensile stress in their specimen, because the circumferential stress distributions measured by the Sachs method [8] depicted higher compression stress on the surface and a tensile stress peak below the surface.

Melloy [15] proposed a quench cracking test using the end-quench test specimen in his report in 1965. A transverse crack along the austenite - martensite interface was generated by brine quenching after end-quenching for a given period of time. This interface might be intended to serve as the metallurgical notch from his consideration.

Shimoda [16] considered a cause of quench cracks in full-size rolls using stress distributions by an analytical technique and measurements by the Sachs method [8]. He described the transverse crack generation in the roll occurred at the point, where the maximum tensile stress was produced in the pearlite region, from observing a fracture section. The same explanation on the crack was carried out by Melloy[15]. Also Shimoda and Melloy identified the influence of residual hydrogen content on the crack in the roll.

Toshioka et al. [17] calculated peaks of axial and circumferential stresses at just below the surface and the center of a Cr-Mo steel roll that was imperfectly hardened by using an analytical technique. They also observed quench crack generation from a point just below the surface of a Cr-Mo forged steel roll, 400 mm in diameter, quenched in water from 850°C. They reported that cracks occur when plastic deformation cannot absorb the stress generation.

Kunitake and Sugisawa [18] performed quench cracking tests of ring specimens by spray cooling, and examined crack susceptibility based on "equivalent carbon". The size of their ring specimen was 75 mm outer diameter, 35 mm inner diameter and 10 mm height. Materials of the specimens were Mn steels and Ni-Cr-Mo steels with various compositions. Elements, Al, Nb and B were also added to the Mn steel specimens for evaluating their effects. They reported that the higher degree of purity of steels is effective in decreasing the crack generation rate.

Mikita et al. [19] conducted tests for tool steel specimens, diameters from 10 to 40 mm and austenitizing temperatures from 750°C to 950°C, by quenching in ice water. They reported that only the 25 mm cylinder generated a longitudinal crack when austenitized at 900 and 950°C. In addition, when an annular V-type notch was machined on the central part of the cylinders and the austenitizing temperature was set to 900°C or greater, a longitudinal crack occurred in all the specimens.

Mikita et al. [20] investigated different crack types by drilling a large hole in a cylindrical test specimen, 25 mm in diameter and 25 mm long, to create a thin ring, 25 mm outer diameter, 5 mm width, and 1 mm thick, on the one end of the cylinder. This type of specimen was prepared by Chapman and Jominy [13] for their study. Mikita et al. reported that quenching cracks occurred at the root of the ring or on the cylinder surface, or at both positions, depending on concentrations and agitation conditions of polymer quenchants.

Narazaki et al. [21] performed quench cracking tests using disk specimens made from two steels, a carbon steel and a tool steel, with an eccentric hole. They varied water cooling conditions, surface roughness and surface texture and then investigated these influences on crack generation. The specimen in this test was originally shown in the report by Chapman and Jominy [13] and was used for the experiments conducted on quench cracking under the Japan Society for Heat Treatment [22].

## 2. Classification of Quench Cracking Tests

Various quench cracking tests described in the former review section can be classified into the following two categories according to their purposes.

(1) For investigating a cause of cracking

Tests for investigating a cause of quenching cracks are fundamentally focused on the relation between stress distributions and crack generations. Hence simple shapes like a cylinder have been chosen as a specimen for easily estimating a stress distribution in many cases. Generally types of steels, diameters of cylinders, austenitizing temperatures, cooling characteristics of quenchants, etc. are varied for studying their contribution to crack generation i.e. stress distributions. The tests by Scott [5], Buhler-Scheil [7], Nishikiori-Iwaki [9], Isomura-Sato. [14], Shimoda [16], Toshioka et al. [17] and Mikita et al. [19] can be classified into this type of experiment.

(2) For determining crack susceptibility

The crack susceptibility of steels alloys, characteristics of quenchants, etc. may be needed for practical reasons. Tests to address the susceptibility of steels to cracking were devised by Udy-Barnett [10] and Wells et al. [11] as described before. The minimum depth of the notch when cracking was adopted as a "crack susceptibility index". The experiments by Chapman et al. [13] and Kunitake et al. [18] also estimate the crack susceptibility of steels although they do not report a value such as the crack susceptibility index. The limitation of the crack generation was obtained from their test for carbon content in steels, $M_s$, quench hardenability, etc. Kunitake et al. [18] examined the value, which shows the limitation clearly, and then they created the new "effective carbon content" for this purpose.

It is useful to make the following classification of the specimens according to the dimension of geometric models for simulation.

(1) one-dimensional models: for a center part of cylinder.

(2) two-dimensional models: for a cylinder, a stepped cylinder with 2 different diameters, a cylinder with a thin ring, a disk, a ring, etc.

(3) three-dimensional models: for a disk with an eccentric hole, a notched-cylinder, a notched-disk, a notched-ring, etc.

In quenching a cylinder with a sufficient length, its center part can be treated as a one-dimensional model having only the radial variable for observing the phenomenon in the section. However a two-dimensional model is needed for examining the cracks at the edges of the cylinder. One or two-dimensional models are recommended for case studies because of restrictions of the calculation time.

## 3. Quench Cracking Simulation

The heat treatment simulation is useful for predicting the metallic phases, temperatures, stresses, strains and distortions during the processes. Since many researchers have indicated that stress distributions contribute to quench cracking, simulated stresses may be utilized for predicting its generation.

Here, a simulation was applied to the several successful cracking tests of cylinders for investigating a cause of their generation. Tendencies of cracking phenomena in the tests were explained using the simulated results. For the more complex shape than a cylinder, the works by Arimoto et al. [3, 4] was used for considering the origin of cracks.

### 3.1 Cylindrical Specimens

Software used for the simulation of cylindrical specimens was verified by comparing experimental and simulated stress distributions in quenched cylinders by the procedures shown in the report by Arimoto et al. [23]. The effect of transformation plasticity to stress distribution was examined carefully according to the studies by Denis et al. [24] and Rammerstorfer et al. [25].

One-dimensional axisymmetric elements were applied to describe the phenomenon in the center part of the cylinder. The heat transfer coefficient on the surface during quenching was estimated using cooling curves of silver probe by the method proposed by Narazaki et al. [26]. Material data and heat transfer coefficients set for these simulations were not so strict because these were just for the preliminary studies.

Table 1 Composition (mass %) of Tool Steel

| Steel | C | Si | Mn | P | S | $M_s$(C) |
|---|---|---|---|---|---|---|
| SK6 | 0.73 | 0.31 | 0.34 | 0.013 | 0.015 | 248 |
| SK5 | 0.82 | 0.30 | 0.41 | 0.013 | 0.016 | 215 |
| SK4 | 0.94 | 0.21 | 0.44 | 0.017 | 0.021 | 174 |
| SK3 | 1.05 | 0.24 | 0.38 | 0.021 | 0.016 | 136 |

### 3.1.1 Effect of Steel Alloys

Isomura and Sato [14] performed the quench cracking test using cylindrical specimens made from four carbon tool steels of the Japanese standard, SK3, SK4, SK5, and SK6. Chemical compositions of the steels are given in Table 1. The specimens, 18mm diameter and 100mm long, were quenched into water after 30 minutes heating at 900, 950 or 1000°C. Each test was conducted five times under the same condition. Table 2 shows the results of their cracking tests. For example, only the SK6 steel specimen did not generate quenching cracks when austenitizing at 1000°C.

The simulation was applied to the tests using the specimens made from all types of steels, however, only 1000°C was selected for the austenitizing temperature. In this simulation, thermal properties of steels were reproduced from the data by BISRA [27]. Mechanical properties of steel were derived from data of the steels having similar compositions. $M_s$ of the steels was calculated by the empirical equation by Kunitake et al. [28] as shown in Table 1. The kinetics of martensitic transformation was described by the Koistinen-Marburger equation [29].

The simulated circumferential stress distributions after quenching are shown in Fig. 1. For the comparison, the measured circumferential residual stress for the SK6 steel cylinder quenched from 1000°C by Isomura and Sato [14] are indicated by the dotted lines as shown in Fig. 1. Tendencies of the stress distributions in the SK6 steel specimen by measurement and simulation agree well, because they show compression stress in the core, a tensile stress peak below the surface and compression stress on the surface. Figure 1 also shows the trend that the tensile stress peak moves to the surface and decreases its amount when the steel having the higher carbon content.

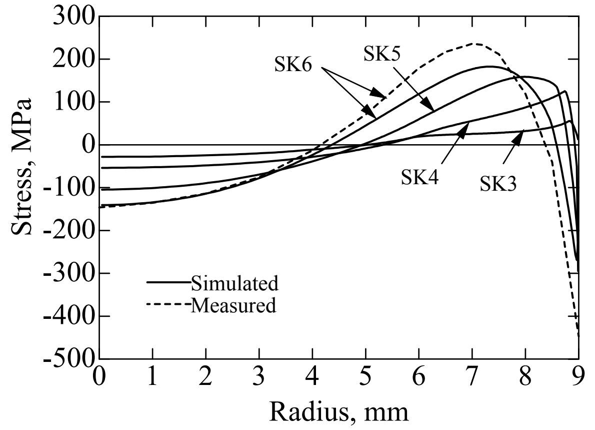


Fig. 1 Circumferential Stress Distribution in SK Tool Steel Specimens

Table 2 Results of Quench Cracking Test for Tool Steel Specimens

| Austenitizing Temp. (C) | SK6 | SK5 | SK4 | SK3 |
|---|---|---|---|---|
| 900 | ○ | ○ | ○ | ▲ |
| 950 | ○ | ○ | ▲ | ▲ |
| 1000 | ○ | ▲ | x | x |

○:No cracked, ▲: Partly cracked, x: All cracked

Isomura and Sato reported that the SK4 steel specimen quenched from 900°C generated a longitudinal crack after removing the surface layer of 0.5 to 0.8 mm by acid corrosion. From their stress measurements, they reported that crack generation in this test originated in the tensile stress peak induced just below the surface. However they also reported that cracks can also initiate on the surface when producing the enough tensile stress to be cracked there.

The tests by Isomura and Sato [14] showed that higher cracking susceptibility is found in the specimens quenched from the higher austenitizing temperature as shown in Table 2. They considered that this crack generation tendency is due to the lower toughness of the martensite produced from the higher temperature austenite according to the Iijima's work. Iijima [30, 31] reported the effect of austenitizing temperature to the toughness of martensite from the measured results by the static torsion test.

### 3.1.2 Effect of Cooling Characteristics

Isomura and Sato [14] quenched cylindrical specimens, 18 mm diameter and 100 mm long, made from the bearing steel, Japanese standard SUJ2, under the different cooling conditions. Table 3 shows the chemical composition of the SUJ2 steel of their specimens. They reported that a crack occurred in water quenching after 1 hr heating at 1000°C, while crack generation was not found in oil quenching after 1 hr heating at 1100°C. In addition, although a crack on the same bearing steel specimens was not observed in water quenching after 1hr heating at 900°C, it occurred in water quenching after oil quenching for 5 to 20 s.

Table 4 describes the results of cracking tests when

Table 3 Composition (mass %) of Bearing Steel

| Steel | C | Si | Mn | P | S | Cr |
|---|---|---|---|---|---|---|
| SUJ2 | 0.98 | 0.30 | 0.36 | 0.012 | 0.006 | 1.39 |

Table 4 Results of Quench Cracking Test for Bearing Steel Specimens

| Water quenching | Oil cooling period (s) | | | | | |
|---|---|---|---|---|---|---|
| | 5 | 10 | 15 | 20 | 30 | 60 |
| ○ | ○ | ○ | x | ○ | ○ | ○ |
| ○ | x | x | x | x | ○ | ○ |
| ○ | x | x | x | x | ○ | ○ |

○:No cracked, x: cracked

austenitizing at 900°C for each different cooling condition. Three rows in the table mean that each test carried out three times under the same condition. For examples, the table explains all three specimens cracked in water quenching after 15 s period of oil cooling.

Figure 2 shows the simulated distributions of circumferential residual stress for the different cooling conditions after 1 hr heating at 900°C. The tendencies of the stress distributions after water and oil quenching agree with experimental results austenitized at 850°C reported by Isomura et al. [14]. The highest tensile stress was calculated on the surface in the condition combined by oil quenching for 30 s and water quenching, although there were no cracks in the tests as shown in Table 4. However cases of oil quenching for 10 to 35 s show the higher tensile stress on the surface than that of only water or oil quenching.

Buhler and Scheil [7] observed a crack by the similar combined cooling condition, initially cooled in furnace and then quenched in water, as mentioned in the former review section. Their measured stress distributions showed the tensile stress on the surface.

In this simulation, $M_s$ data was based on the study by Grange and Stewart [32]. Their measured curves on the martensite formation in the 52100 bearing steel can be used to define that $M_s$ for austenitizing at 843 and 1066°C is 241 and 115°C, respectively for use as a parameter of the Koistinen-Marburger's equation [29]. $M_s$ for austenitizing at 900°C was set at 209°C by interpolating the above two values for this simulation. Grange and Stewart considered that the difference of $M_s$ was due to the austenitizing temperature caused by the influence of undissolved carbide content in the austenite. The same phenomenon regarding $M_s$ was reported by Harris and Cohen [33]. This kind of effect may also occur in the SK steels. Hence the estimated $M_s$ values for the SK steels by the empirical equation should be used keeping this fact in mind. It is also known that $M_s$ affects stress distributions from the simulated results by Arimoto et al [23].

3.1.3 Effect of Specimen Size

Mikita et al. [19] performed tests for examining the effect of specimen size to quench crack generation. Cylindrical specimens were made from the Japanese standard SKS3 steel, containing 0.98%C, 0.8%Cr. and 0.7%W. Their diameters varied from 10 to 40 mm in 5 mm increments and their length was 4 times each diameter. The specimens were quenched in ice water after heating in a furnace and preventing oxidization and decarburization. They reported that only the 25 mm cylinder produced a longitudinal crack when austenitized at 900 and 950°C, in once per five tests under the same conditions.

For the simulation, thermal, mechanical and transformation properties were derived by the same procedure of the SK steels, except $M_s$, 153°C, was referenced from the TTT diagram of 105 WCr 6 steel in the data book compiled by Max-Planck-Institute [34].

Figure 3 shows the circumferential residual stress distributions obtained from the simulation for the different diameter specimens quenched from 900°C. The peak of tensile stress on or below the surface of the specimens increases in the larger diameter specimen. However, a very narrow region of decreasing stress appeared below the surface of the specimen greater

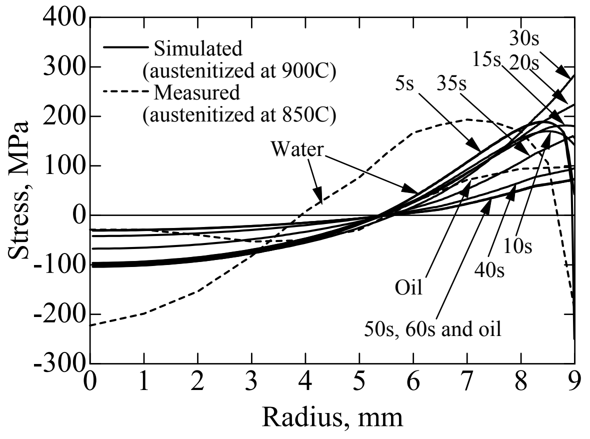


Fig. 2 Circumferential Stress Distribution in SUJ2 Bearing Steel Specimens

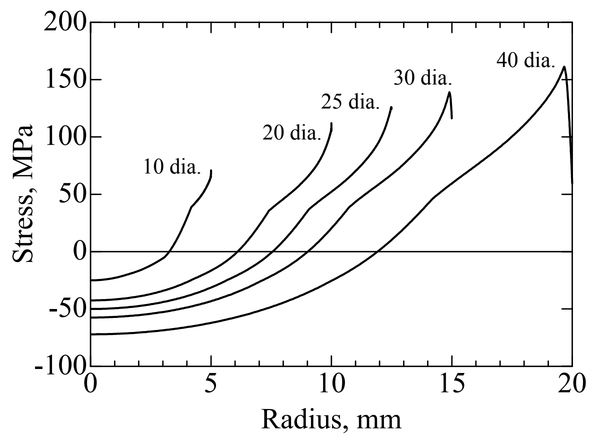


Fig. 3 Simulated Circumferential Stress Distribution in SKS3 Tool Steel Specimens

than 30 mm in diameter.

The above-simulated results may be not enough to explain the reason why cracks occur in the limited diameter of the specimen. This should not be concluded without measuring the stress distribution. The similar tendency of the diameter effect shown in Fig. 3 was found in the measured residual stress distributions in 1.1%C steel cylinders, 5, 7 and 9 mm in diameter, water quenched from 900°C by Fujisawa [35]. His 7 and 9 mm diameter specimen showed the decreasing stress range below the surface, although the range was not observed in the 5 mm diameter case.

Mikita et al. reported only the 25mm diameter specimen generated a crack. However Scott [5] mentioned that cracks occurred in the diameter range between 1/4 in. (6.4 mm) and 1/2 in. (12.7 mm) of the cylinders, made from tool steel containing 0.9%C, 1.2%Mn, 0.2%Si, 0.5%Cr and 0.5%W, by water quenching from 850°C.

### 3.2 Complex Shape Specimens

Cylindrical specimens have been used for the studies on the cause of the quench cracking for many years, because only their stress distributions can be measured. However, quench cracks occurring in more complicated shapes may be caused by another situation. For considering this kind of crack, simulated results for a stepped cylinder and a disk with an eccentric hole were used.

A quench crack on the stepped cylindrical specimen made from the 2%Cr steel was observed by Inoue at al. [36], and its generation was simulation by Arimoto et al. [3]. This specimen had a step by combining two cylinders, 100 mm and 50 mm in diameter, and 100 mm and 20 mm length, respectively. A circumferential crack occurred on the middle of the step surface of the specimen during water quenching from 1200°C. Simulated results showed that a concentration of the radial tensile stress distribution occurred on the step surface near the cracked location at 150 s after starting the quench. It was also clear from simulated results that the martensite was almost transformed in this position.

The quench cracking of the disk with an eccentric hole was simulated by Arimoto et al. [4]. This simulated disk test was selected from the research by Narazaki et al. [21]. The disk made from Japanese SK4 tool steel, 30 mm in diameter and 10 mm thick, contained an eccentrically located 10 mm diameter hole at 8 mm distance from the center. Quench cracks occurred near the hole of the disk at 4 s after starting the quench. A concentration of the tensile stress distribution of the maximum principle stresses was appeared at the position where a crack generated and at the time of its initiation in the simulated results. It was also observed that martensitic transformation was almost completed in the cracked location.

The above two examples may be typical case of the quench cracking in more complex shape when it occurs during cooling. The origin of these cracks may be from a high tensile stress concentration on the surface of the part transformed to the martensite due to the thermal contraction and/or transformation expansion during cooling. The position, which induced a concentration of tensile stress in the complicated shapes, depends on the shape of the work and the distribution of thermal, transformational, plastic and transformation plastic strains. It may be different from that when simple outer loads are applied to the part.

Other simulated results on the quench cracking in complicated shapes have not been found by the authors. In the notched simple shape specimens tested by Udy et al. [10] and Wells et al. [11], the stress distribution near the notch may contribute to the crack generation from the experimental results. However, under the current simulation environment, it is thought that the case studies for the notched specimens require too much time.

## 4. Quench Crack Prevention by Computer Simulation

The simulation technique is expected for preventing the quenching cracks, while the conventional experimental methods are still used for the practical cases. As already stated, this technique is to predict crack generation using the simulated stress. Here, the subject for the utilization of the quench crack prevention by computer simulation is summarized.

### 4.1 Quench Crack Tests for Verifying the Simulation

The simulation of quench cracking is still in the beginning stage. Its potential is evaluated by application to several problems. Detailed comparisons with experimental and simulated results are needed for verifying the simulation technique. Although the past experiments for investigating the cause of cracks may be meaningful, these were not conducted in a position of the comparison with the simulation. Hence the reported data is not sufficient for verification, and these tests should be performed again. The following cracking tests serve as candidates of re-examinations.

(1) A longitudinal crack on the cylinder

Conditions of the crack generation in the tests using cylindrical specimen are comparatively clear. For example, there are tests by Isomura-Sato [14], Mikita et al. [19], Nishikiori-Iwaki [9], Scott [5], etc.

(2) A circumferential crack on the step surface of the stepped cylinder

This type of crack occurs in the stepped specimen during cooling [36]. The circumferential crack on the step surface may be easier to examine by the two dimensional simulation.

(3) A transverse crack in the one-end quench specimen

This transverse crack was observed by Melloy [15]. Since this cracking test has high reproducibility and its fracture surface is simple, the test results may be useful for making a criterion of the crack generation.

It is recommended that other tests using more complicated shape specimens should be tried after the above three examinations because of their complexity.

In the test, the following points take into account for deriving precise measurements.

(1) Contents of the specimen material are analyzed strictly. The characteristics data for the simulation like TTT diagram, $M_s$, stress-strain relations, etc. is collected by the tests.

(2) Cooling curves at the several points in the specimen are measured by thermocouples. They are utilized for predicting heat transfer coefficients along the surfaces of the specimen for the simulation [26].

(3) For the specimens without cracks after quenching, the measurement of stresses and distortions are recommended for verifying the simulation. The Heyn method [6] and Sachs method [8] can be applied for the stress measurement in cylinders, while the X-ray method and the neutron method [37] are useful for more complicated specimens.

(4) For the specimens with cracks after quenching, fracture surfaces are examined by the fractography for determining a beginning point of cracks.

(5) A crack generation time is measured during quenching for comparing the time of inducing a concentration of the tensile stress in a specimen by simulation. There are examples which detected the generation time by the measurement of sound or vibration [19].

### 4.2 Criterion of Quench Crack Prevention

If the stresses in quenched works are found with sufficient accuracy during processes by simulation, a problem comes out for judging quench crack generation from the simulated results. Our goal is to establish a criterion what types of stress states can prevent the quench crack generation in a certain steel product. It is thought that the following items are required for the work.

(1) The measurements of strength and toughness in martensitic phase are needed for the practical steels. For example, we have such kind of data, torsion strength, plastic torsion angle and absorbed energy, were derived from the static torsion test for several carbon steels and low alloy steels by Iijima [30, 31].

(2) Since the quench cracking is a brittle fracture phenomenon, it is necessary to examine characteristics of this destruction. For example, there are degrees of steel purity, surface notches, nonmetallic inclusions, segregations, metallurgical notches, etc.

(3) For cracks which occurred in the middle of the quenching, the thermal shock characteristics of loads, i.e., the rate of stress changes, and distribution patterns of the stress concentrations might be considered for the evaluation.

## 5. Conclusions

Considerable research on quench cracking has been performed to obtain a thorough and correct understanding of this phenomenon and its prevention. In this study, preliminary work for establishing a criterion of crack prevention by heat treatment simulation was conducted resulting in the following conclusions:

(1) The prediction of the stress state at the time of the quench crack generation is possible by simulation, although a few examples are found.

(2) For the present, it is necessary to increase the applications of quench crack predictions by a comparison between repeated experiments of the successful tests and their simulated results.

(3) Since much work is needed for establishing a criterion of quench crack prevention, a systematic full-scale research program will be required.

The thermal process simulator, FINAS/TPS, developed by CRC Solutions Corp., was used for the simulation in this study.

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