Journal of Science & Technology 119 (2017) 043-047

Effect of Quenching Media on Distortion of C-Ring Specimen Made by 100Cr6 Steel - Simulation and Experiment

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Received: December 18, 2016; accepted: June 9, 2017

Abstract

Polymer quenchants based on polyalkylene glycols (PAG) are currently the most widely used type of aqueous quenchants. In this paper, the numerical simulation method by Sysweld software was used to predict the distortions of C-ring model using 100Cr6 steel when quenched in the difference media. The simulation results are in good agreement with the experimental values, and they also showed that the top of C-ring was opened after deformation. The gap opening of C-ring specimens when quenched in PAG 20% solution is the smallest in comparison to the specimens quenched in water, oil and PAG 10% solutions. On the other hand, the research results also show that the distortion at the top of C-ring is the largest and they are decreased from the top downward the bottom of C-ring.

Keywords: Distortion, quenching, numerical simulation, C-ring, 100Cr6 steel, poly(alkylene glycol)

1. Introduction

Heat treatment is used to improve some of the mechanical properties of steel components, and commonly involves a quenching step which may cause undesired geometrical distortions in the processed parts. The dimensional accuracy of these parts is affected and leads to production and economic losses. An example of this situation is the production of rolled and heat treated rings with large diameters and small thickness, quenching causes out-of-roundness of the rings.

In quenching process, the quenchant (namely the heat transfer coefficient of quenchant) decided to microstructure, hardness, residual stresses and distortion of quenched components. Requirements set that the quenchants must have the high enough of the cooling rate to transform austenite into martensite with the very high hardness, at the same time they have the small enough of the cooling rate to limit the distortion of quenched details. Therefore, the research in order to limit the distortion of the steel parts when quenching is very important.

The oil quenchants are often used, but they present both fire and smoke hazards. For many years, water-in-oil emulsions were used to obtain better fire-resistance but these fluids were particularly susceptible to biological attack. Water quenchants although harmless and cheaper, but the very high cooling rate of its can cause the crack in quenched components and therefore it is not appropriate to quench some kind of materials. Subsequently, polymer quenchants were developed and are used to control distortion and to prevent the crack in steel parts during the quenching process. Currently, a number of polymers have been used as the quenchants for heat treating applications. These include: poly(vinyl alcohol), poly(alkylene glycol), Poly(acrylamide), polyvinylpyrolidine, poly(sodium acrylate), poly(ethyl oxazoline). Of these, the most commonly used are poly(alkylene glycol) – PAG, poly(vinyl pyrrolidone) – PVP, and poly(ethyl oxazoline) – PEOX. However, the most common quenchants encountered for induction heat treating applications worldwide are PAG type [1].

The simulation of metal heat treatment was studied by some authors, but the simulation of fully mechanical – physical – metallurgical behavior is researched by the very little author, because of the limit of the simulation software and computer capacities. Among the commercial simulation software today, Sysweld software is considered as the strongest and most complete application for the heat treatment of metals. For deformation problems, Sysweld not only calculates the distortion due to thermal expansion as other software, it also calculates the distortion caused by the phases transformation as shown in Fig. 1. [2].

Based on above advantages, the Sysweld software was selected to simulate the distortion of C-ring model made by 100Cr6 steel when quenched in various media, they are including water, oil and PAG liquid solution of 10% and 20%. After simulation, the results are verified by experiment.

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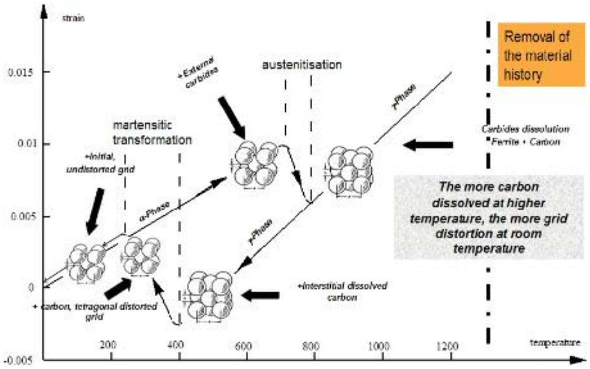

Fig. 1. The strain (distortion) caused by phases transformation in steel [2]

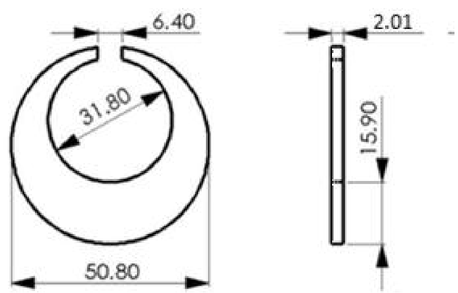

Fig. 2. Geometry and dimensions of C-ring (all dimensions in mm)

2. Methodology

2.1 Modeling of the quenching process

The testing of the Navy C-ring type was described by Narazaki and Totten (2006) as a procedure to evaluate the propensity for quenching distortion in several materials. M. Manivannan et al (2014) used this test to study and predict the distortion in heat treatment components [3]. Until now, the C-ring has been one of the most common types of specimen used for observing the dimensional changes (distortion) after heat treatment. In this research, the shape and dimensions of the C-ring specimen are given in Fig. 2. The material employed for the C-ring specimen was a 100Cr6 (DIN 17230) with the nominal chemical composition (certified by the supplier) of 1.04% C, 0.26% Si, 0.33% Mn, 0.31% Ni, 1.53% Cr, 0.01% Mo, 0.01% Mo.

Using Sysweld software to discrete the C-ring model in Fig. 2, we get the finite element model as shown in Fig. 3. Here, by the cross section of the model have the curve, so to ensure the accuracy when meshing the model, the authors use element type has curved edges. On the other hand, in the direction of thickness, the model has a uniform cross-section shape, so the element type with the straight edge will fit in the direction of thickness.

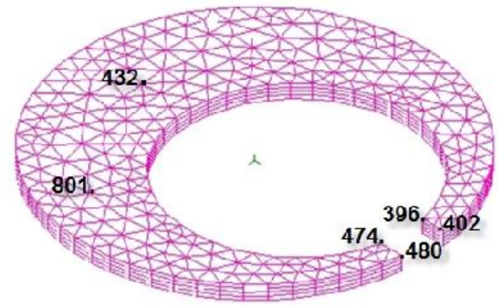

Fig. 3. FEM model of the C-ring specimen.

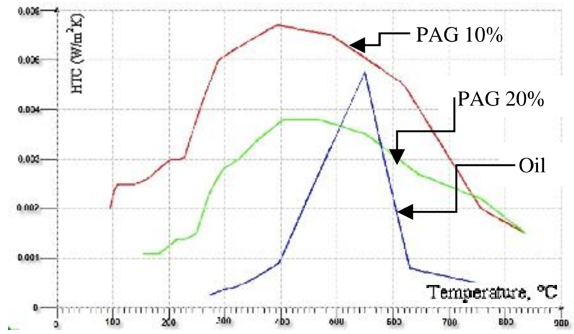

Fig. 4. HTC of some quenching media

Fig. 5. HTC of water quenchant

Combine the two features mentioned above, the author uses the type of element which has 5 faces and 15 nodes with straight and curved edges combination for meshing the C-ring model. To achieve the necessary precision, the size of the elements must be small enough [4] and in this study, the model has meshed with the biggest element edge is 2 mm.

To build the simulation project, the model must also be assigned a full set of parameters on the mechanical - physical - metallurgical properties of the material and the other simulation conditions. For the problem of quenching, the heat transfer coefficient (HTC) at the surface of the model which is the boundary condition of simulation. The value of an HTC function at the surface of the model is determined by experiment and will be incorporated into the Sysweld software to simulate (Fig. 4, 5):

2.2 Experimental Procedure

The C-ring specimens were heated up to 850 °C in Nabertherm (Germany) furnace and held at this temperature for 20 minutes. Then, the samples are quenched in the water, oil and PAG quenchants of 10% and 20%.

The measurement of the C-ring dimensions before and after the heat treatment was performed on the coordinate measuring machine, model *УИМ21* (Fig. 6) with an accuracy of 0.001 mm. The dimensional change was analyzed: gap opening G based on Fig. 7, the dimensional change may be expressed as: G = n' – n

Fig. 6. Universal Microscopy УИМ21

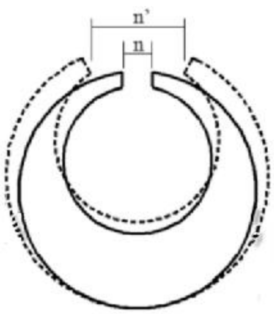

Fig. 7. C-ring specimen in before (gap opening n) and after (gap opening n') quenching.

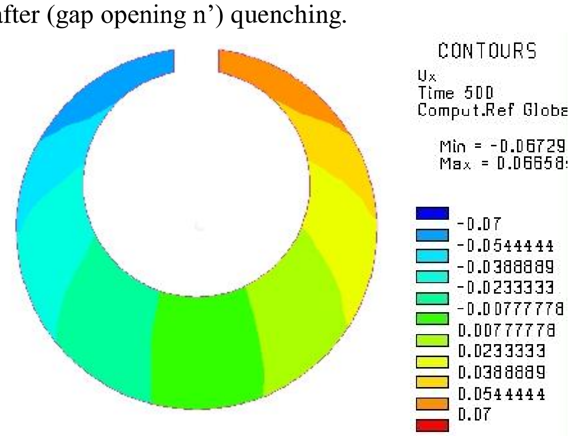

Fig. 8. Simulated displacements in the x direction of the C-ring, after quenched in PAG 10% solution

3. Results and Discussion

Using Sysweld software to perform the simulation of quenching process for the model in Fig. 3 with the full material parameters of 100Cr6 steel and boundary conditions as shown in the Fig.s 4 and 5, we have determined the distortions of the model after quenched 500 seconds corresponding to the quenchants as follows:

3.1. Distortion of the C-ring specimen when quenched in PAG 10%

Fig. 8 displays the simulated displacement in the x direction of the points in the cross-section of the C-ring which is quenched in PAG 10% solution. The results show that in the right half of C-ring model, the nodes are displaced in the positive direction of the Ox axis and in the left half of C-ring, the nodes are displaced in the negative direction of the Ox axis. Thus, the distortion on the specimen tends to open up the C ring. The node 480 is displaced along the positive direction of the Ox axis with a distance of approximately 0.066 mm, while node 402 is displaced along the negative direction of the Ox axis with the same distance. It means that the gap opening of the C-ring is about 0.132mm. The simulated results in Fig. 8 also show that the distortion of C-ring specimen decreases from the top (node 480) to the bottom (node 432). At the node 801, the displacement is about 0.02 mm and the displacement of node 432 is nearly zero.

The comparison between the experimental and simulated values for the distortion of C-ring when quenched in PAG 10% solution as shown in Table 1. The compare shows that the relative difference for gap opening is smaller than 4%.

Table 1. Comparison of experimental and simulated distortions of the C-ring after quenched in PAG 10%

Quenchant	Gap opening (G) (mm)		Difference (%)
	Experimental	Simulation	
PAG 10%	0.128	0.132	3.03

3.2. Distortion of the C-ring specimen when quenched in PAG 20%

The computation results of displacements in the x-direction of the points in the cross section of the C-ring model when quenching in PAG 20% as shown in Fig. 9. In this case, the computation results show that the biggest displacement in the x direction (Ux) is 0.043 mm, achieved at node 480 and displacement at the node 402 is -0.043 mm. It means the gap opening of the C-ring is about 0.086 mm. The computation results in Fig. 9 also show that the Ux distortion at the bottom zone of the C-ring is the smallest, namely the displacement of the node 432 is zero.

Comparing these results with the sample results are quenched in PAG 10% solution we can see that in this case, the samples have the smaller deformation. This means that when quenching in polymer quenchants if the concentration of polymer is higher then the distortion of the sample is smaller. This can be explained by the cooling rate of the specimen to be quenched in PAG 20% is lower than it has been quenched in PAG 10% [5].

Table 2. Comparison of experimental and simulated distortions of C-ring after quenched in PAG 20%

Quenchant	Gap opening (G) (mm)		Difference (%)
	Experimental	Simulation	
PAG 20%	0.08	0.086	7

Table 3. Comparison of experimental and simulated distortions of C-ring after quenched in water

Quenchant	Gap opening (G) (mm)		Difference (%)
	Experimental	Simulation	
Water	0.176	0.18	2.2

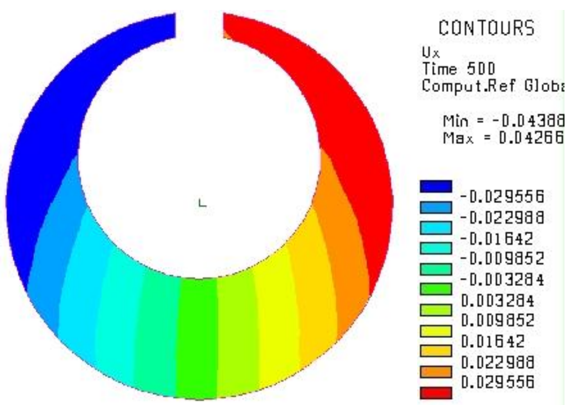

Fig. 9. Simulated displacements in the x direction of the C-ring, after quenched in PAG 20% solution.

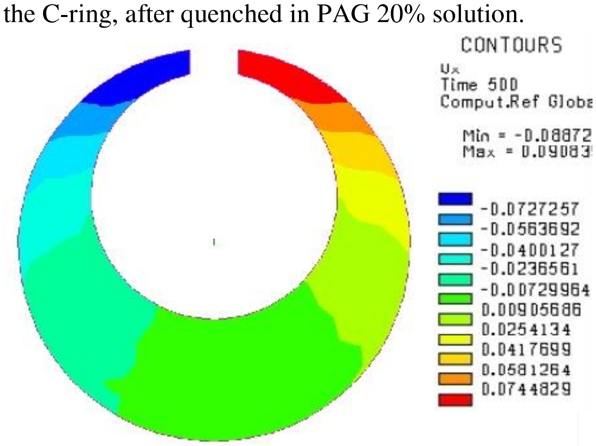

Fig. 10. Simulated displacements in the x direction of the C-ring, after quenched in water.

Table 2 presents a comparison between the experimental and computation values for the distortion of the specimen when quenched in PAG 20% solution. In this case, the gap opening computation result of the C-ring is only of 0.086 mm and the measuring result on the coordinate measuring machine is 0.08 mm. Thus, the corresponding error, in this case, is 7%.

3.3. Distortion of the C-ring specimen when quenched in water

With such samples, in water heat treatment as we obtain the results as shown in Fig. 10. The simulation results in this case also reflect a trend of deformation of the sample is similar to the heat treatment in the polymer quenchants. That is, after quenching, the C-ring samples are also deformed with trend opens and the deformation of the sample is also distributed symmetrically through the center. The nodes in the right half are moved in the positive direction of the Ox axis, while the nodes in the left half are moved in the opposite direction, making the sample was opened - This is like observing in experimental samples. The simulated deformation in Ox direction at node 480, in this case, is 0.09 mm and -0.09 mm at nodes 402. That is the gap opening of the C-ring is 0.18 mm. Comparing these results with the results of the specimen to be quenched in PAG 10% and PAG 20% solution, we see that the samples, in this case, have the greater deformation. It is caused by the cooling rate of the sample when quenched in the water is higher than PAG solution [6].

Compare the measuring gap opening of the C-ring with the simulated values when quenched in water, we received the result as shown in Table 3. In this case, the relative difference for gap opening is smaller than 3%.

3.4. Distortion of the C-ring specimen when quenched in the oil

When the simulation of the quenching process of the research model in traditional quenchant is oil, we received the displacement in an x-direction of the C-ring model as shown in Fig. 11. Like the simulated results of the quenched model in water, PAG 10% and 20%, when the specimen was quenched in oil, the displacement in the x-direction at node 480 is also largest (about 0.059mm). In this case, the gap opening of the C-ring model is about 0.118 mm. Thus, the distortion of the C-ring model, when quenched in oil, is smaller in compare with the model which quenched in PAG 10% and water, but larger than the quenched model in PAG 20%.

The comparison between the experimental and simulated distortions of the C-ring when quenched in oil as shown in Table 4. It is seen that the relative difference for gap opening is smaller than 5%.

The simulated and measured distortions of the C-ring specimens, when they were quenched in the different quenchants, are shown in Fig. 12. We see that if the specimen is quenched in water then the gap opening of C-ring is largest; whereas if that was quenched in PAG 20% solution, it will have minimal distortion.

Table 4. Comparison of experimental and simulated distortions of C-ring after quenched in oil.

Quenchant	Gap opening (G) (mm)		Difference (%)
	Experimental	Simulation	
Oil	0.113	0.118	4.2

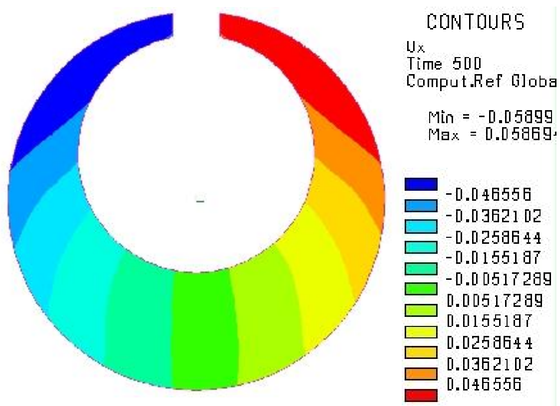

Fig. 11. Simulated displacements in the x direction of the C-ring, after quenched in oil.

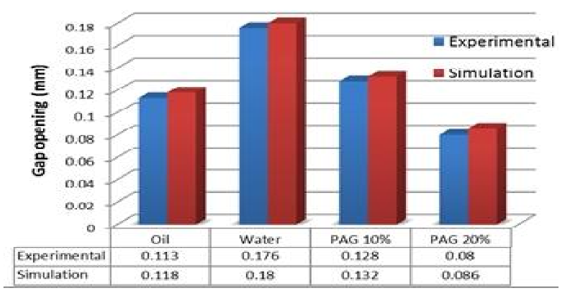

Fig. 12. Comparison of distortion when quenched in different quenchants: simulation and experiment.

The simulated and measured results also shown that the distortion of the specimen, when quenched in PAG 10%, is nearly equal to the distortion of the sample when quenched in the oil. In the process of measuring the deformation, due to the device's accuracy and the operator's subjective factors, the heat transfer coefficient is additionally calculated based on the simulation software through the cooling speed value provided by experimental measurements. These factors can also lead to some minor differences between experiment and calculation. These results also reflect the properties of the quenching media as shown in the Fig.s 4 and 5: the HTC of the specimen to be quenched in PAG 20% is smallest, it will have minimal distortion.

Acknowledgments

This research is funded by Hanoi University of Science and Technology (HUST) under project number T2016-PC-150.

4. Conclusions

Based on the simulation and actually measuring results of C-ring deformation above, the following conclusions can be drawn:

The simulation results based on finite element method are in good agreement with the experimental values. The maximum difference between the experimental and the simulated values for the C-ring gap opening was only about 7%. I.e. above simulation method is accurate and reliable.

The gap opening of the C-ring specimen that quenched in PAG 10% solution is smaller than the specimen quenched in water but larger than quenched specimen in oil.

The quenching distortion of C-ring specimen is the largest at the top (including the nodes 480, 402, 474 and 396) and decreases to zero at the bottom of C-ring (node 432).

With PAG 20% aqueous solution, the gap opening of the quenched C-ring specimen is the smallest. i.e. the PAG 20% quenchant is most suitable to quench the 100Cr6 steel when compared with oil, water or PAG 10% quenchants.

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