# Minimizing Distortion During High Pressure Gas Quenching Processes

**Zhichao (Charlie) Li, Justin Sims, and B. Lynn Ferguson**
DANTE Solutions, Inc.
Cleveland, Ohio, USA

**Jason Fetty, and Treven Baker**
US Army
Aviation Development Directorate
Fort Eustis, VA, USA

## ABSTRACT

Steel components, such as gears for rotorcraft transmissions, are quench hardened to improve the hardness, strength, and fatigue performance. During a quench hardening process, components are heated to form austenite, followed by quenching (either gas or liquid) to transform to hard martensite. With High Pressure Gas Quenching (HPGQ), parts are rapidly cooled by using a pressurized gas such as Nitrogen or Helium. Hardening is a highly nonlinear process due to the plastic deformation caused by thermal stresses and phase transformations, both of which lead to distortion. Reducing distortion caused by hardening has always been pursued by heat treaters for the purposes of improving part quality and reducing cost. A new gas quenching method to minimize distortion of Ferrium C64 gear steel was developed by DANTE Solutions as part of an effort with the US Army's Aviation Development Directorate (ADD). This method utilizes a new state-of-the-art gas quench chamber to control the temperature uniformity of parts using a recipe developed through computer modeling.

## INTRODUCTION

During quench hardening, the internal stresses generated by the thermal gradient and phase transformation create plastic deformation. This plastic deformation ends up as distortion in the final hardened parts. Hardened components with distortion in the allowable range can be straightened or ground. However, the straightening and grinding processes can affect the beneficial surface compressive residual stress and the uniformity of the carburized case. It is critical to reduce the magnitude of distortion, so that only a minimal amount of grinding or even no grinding will be needed.

Distortion caused by quench hardening can be divided into shape change and size change, based on their different mechanisms, which can be characterized by computer modeling [Ref 1, 2]. Shape change is the part dimensional difference before and after hardening with the assumption of no volume change. The size change is the part size (volume) difference before and after hardening. Size change is caused by the material microstructure change, with the different microstructural phases having different densities. For example, with ferrite/pearlite microstructure as initial phases prior to hardening, and martensite phase being the final phase after hardening, the part volume will expand because the martensite has a lower density. Gear steels also typically undergo carburization before quenching, where carbon is absorbed into the surface of the base steel material. By introducing carbon into the part surface, the material will expand due to dilation of the steel matrix. The size change caused by microstructure differences before and after hardening is unavoidable, but it can be accounted for through the heat treatment part configuration design with the help of computer modeling.

Under this effort, a prototype gas quench chamber, called the DANTE Controlled Gas Quench (DCGQ) has been designed and fabricated, and it is being tested. The objective of this DCGQ is to minimize the distortions of components during heat treatment. The mechanical properties, including hardness, tensile properties, impact strength, and fatigue performance of parts processed using the DCGQ system must be equivalent to parts manufactured using a standard HPGQ process. With reduced distortion, while meeting the required mechanical properties, it is possible to significantly reduce post-heat treat machining, so the beneficial surface residual stress will not be damaged. This paper will summarize the use of modeling tools to develop new gas quenching recipes to reduce distortion, provide an overview of the DCGQ system, and provide test results that

Presented at the AHS International 74th Annual Forum & Technology Display, Phoenix, Arizona, USA, May 14-17, 2018.

demonstrate a reduction in distortion while maintaining the mechanical performance.

## CAUSES OF DISTORTION DURING HPGQ HARDENING PROCESS

Using a simplified thin-wall ring gear example shown in Figure 1, the causes of the shape distortion from nonuniform cooling and phase transformation are demonstrated schematically by using measured time-temperature cooling curves and computer modeling [Ref 3].

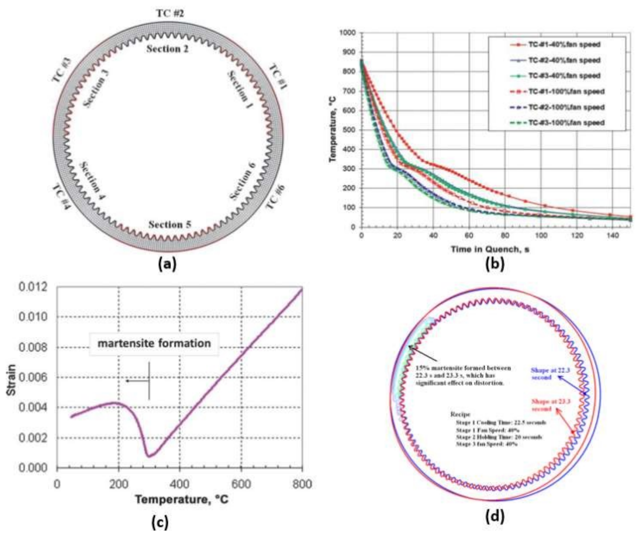



**Figure 1. Effect of cooling nonuniformity and phase transformation on distortion. (a) Schematic description of thermocouple experimental set up, (b) Recorded cooling history using thermocouples, (c) Demonstration of material volume expansion with martensitic phase transformation, and (d) Nonuniform martensitic transformation in the gear wall during quenching.**

During a HPGQ process, the gas flow pattern is affected by the chamber/nozzle design, the part configuration, and the fixture design, etc. As shown in Figure 1(a), the thin-wall ring gear has six thermocouples embedded evenly in the circumferential direction. The recorded data shows significant cooling difference at different locations, as shown in Figure 1(b). The flat region of the cooling curves is caused by the latent heat released during the martensitic phase transformation. The temperature difference between the TC#1 and the TC#3 can be as much as 100° C. In quenching chamber and part racking designs, a gas flow pattern along the axial direction of the gear is preferred. However, this may not be achievable in a practical heat treatment process. With various cooling rates at different locations, the martensitic transformation timing will be different spatially. Figure 1(d) shows a snapshot of martensite distribution during quenching. At this specific time, the martensitic transformation has started on left side of the gear, while the temperature on the right side is still above the martensite transformation starting temperature ($M_S$). It is known that the material volume expands with martensitic transformation, as shown in Figure 1(c), and the material will be in a plastic deformation condition with phase transformations occurring. Nonuniform phase transformation in the part will cause distortion in the quench hardened part.

## DANTE CONTROLLED GAS QUENCH (DCGQ) APPARATUS DESIGN FOR REDUCED DISTORTION

During a HPGQ process, the nonuniform cooling around the part is caused by one or more factors: 1) variation of gas flow rate and flow direction around the part surface, 2) variation of ambient temperature around the part surface, and 3) nonuniform part geometry (with a combination of thin and thick sections). The nonuniform cooling, leading to nonuniform phase transformation timing in the part, is the cause of distortion after hardening. Researchers have spent a great effort to improve the quenching uniformity of HPGQ chambers [Ref 4, 5]. However, the improvements achieved are limited due to the necessary high flow rate and the low heat capacity of the quenching gas. The low heat capacity of the quenching gas results in a significant increase in the gas temperature during quenching, and the ambient temperature in the quenching chamber is nonuniform. The DCGQ system designed under this research effort controls the ambient temperature of the quenching chamber as a function of time, so the temperature gradient throughout the part can be controlled while martensitic phase transformation occurs.

Using the thin-wall ring gear example shown in Figure 1(a), the effect of nonuniform gas flow on distortion was analyzed using DANTE modeling software. The predicted distortions in Figures 2(a) and 2(b) represent two scenarios using 6 bar nitrogen quenching: a) standard HPGQ process, and b) DCGQ process. An average convection coefficient of 600 $W/(m^2K)$ was assumed for the 6 bar nitrogen quench, and applied for both scenarios. As shown by the arrows in Figure 2, the model assumes that the gas flows from left to right for both scenarios, with the left surface facing the gas flow and the right surface on the back. A 25% higher convection coefficient was applied on the left surface, and 25% lower convection coefficient was applied on the right surface. The applied convection coefficients on the middle surface were linearly interpolated between the front and the back. Again, the same convection coefficients were applied for both scenarios. The difference between the two scenarios was the quench chamber ambient temperature, with the assumption of a constant 20° C ambient temperature for the standard HPGQ process, and the ambient temperature as a function of time for the DCGQ process. The predicted results of radial distortion are shown for the HPGQ process and the DCGQ process in Figure 2(a) and Figure 2(b) with 20 times magnification. The recipe of the DCGQ process was designed using DANTE modeling to reduce the temperature gradient below a specified value when martensitic phase transformation occurs in the part. It is clearly shown that the distortion is greatly reduced by controlling the ambient temperature during a gas quench process.

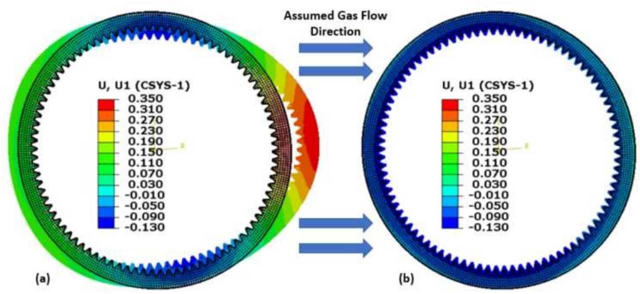



**Figure 2. Comparison of predicted shape change caused by quenching. (a) nonuniform gas flow with standard 2 bar HPGQ, and (b) nonuniform gas flow with controlled ambient temperature recipe. Each figure compares the initial and final shapes.**

Different from an immersion quenching process using liquid media (e.g. oil quenching), the ambient temperature during a gas quenching process can be controlled or designed in terms of time because the gas can tolerate higher temperatures, and the gas can be heated or cooled faster than the liquid quenching media. Figure 3 shows a schematic of the DCGQ apparatus designed to fulfill the function of flexibly controlling the chamber ambient temperature during quenching. Different from the conventional HPGQ system, the DCGQ system has an external heating unit and a heat exchanger in the gas flow system. The combination of the heater and heat exchanger will allow the chamber to be scheduled to a prescribed temperature versus process time recipe. For a specific part geometry with a given steel grade, such as Ferrium C64 for this effort, the required recipe can be designed using DANTE modeling.

While the DCGQ system was being designed, a dual furnace quenching process was used to evaluate the mechanical properties, with the cooling rate obtained from the dual furnace quenching representing that of the DCGQ system. A brief description of the dual furnace quenching process is: 1) austenitize the coupon in one furnace; 2) transfer the coupon from the heating furnace to the second furnace with the furnace temperature being slightly above the martensitic transformation starting temperature (Ms); and 3) once the coupon temperature reaches the furnace temperature, remove the coupon from the furnace and cool to room temperature in still air.

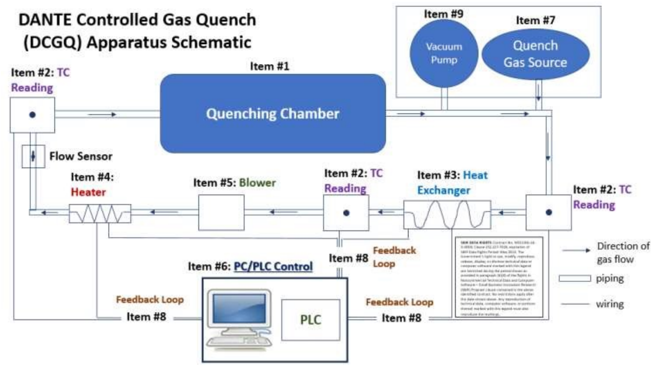
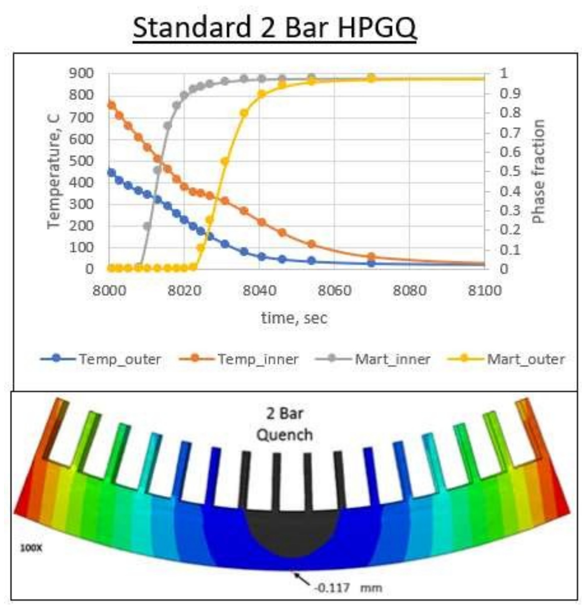



**Figure 3. DANTE Controlled Gas Quench (DCGQ) apparatus schematic.**

A distortion coupon made of Ferrium C64 was designed to demonstrate the effectiveness of achieving reduced distortion using the DCGQ system. As shown in Figure 4, the coupon has multiple fins on one side to purposefully make the cooling on the fin side faster than the opposite side. All three processes, 2 bar standard HPGQ, dual furnace quenching, and DCGQ, were modeled using DANTE, and the modeling results of temperature, phase transformation, and final distortion are shown in Figure 4. The predicted bow distortion is reduced from 117 µm for the standard 2 bar HPGQ to 54 µm for the dual furnace process. With the DCGQ process, the predicted distortion is close to zero. The bow distortions are magnified by 100 times for all three cases.



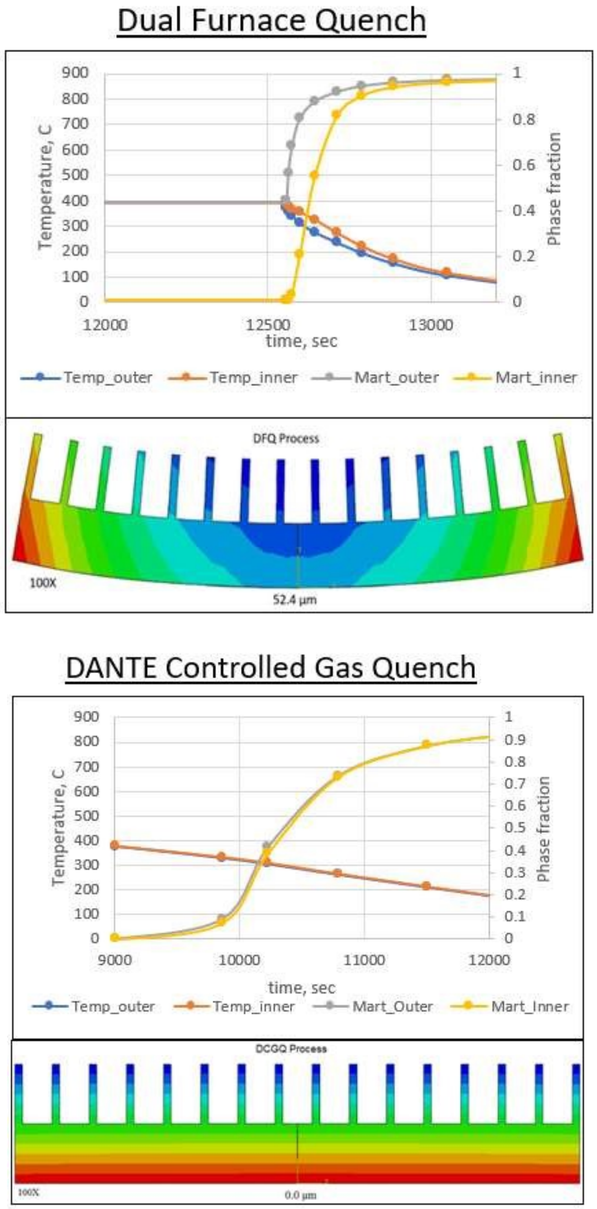



**Figure 4. Modeling proof for reduced distortion using the DCGQ process.**

## MECHANICAL PROPERTY AND BENDING FATIGUE TESTS USING THE DUAL FURNACE QUENCHING PROCESS

It is important to make sure the mechanical properties obtained from the DCGQ process are equivalent to the standard HPGQ process. The obtained mechanical properties are mainly affected by the cooling rate during quenching, provided that each process produces martensite. With the assumption that the cooling rate of the dual furnace quenching is close to that of the DCGQ system, the mechanical properties obtained from the dual furnace quenching process were compared with those from the standard 2 bar HPGQ process. In this study, the high hardenability Ferrium C64 steel was used, so no diffusive phases should be formed.

Figures 5(a) and 5(b) show the two quenching baskets with various coupons for tensile tests, Charpy tests, hardness tests, and bending fatigue tests. They were processed by the 2 bar standard HPGQ and the dual furnace quenching, respectively. Most coupons were copper plated to avoid decarburization, and the coupons were separated for good gas flow. The tensile test and Charpy coupons were further machined after hardening, so they were not copper plated, as shown in Figure 5. After quenching, the coupons went through deep freeze and tempering processes according to the standard processing specification.

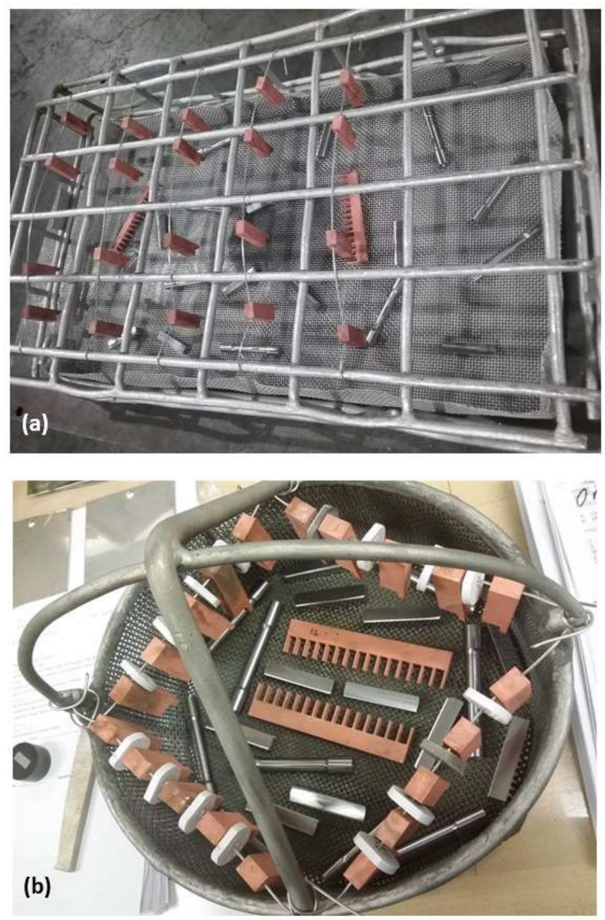



**Figure 5. Quenching baskets. (a) Standard 2bar HPGQ, and (b) Dual furnace quenching process.**

Ferrium C64 has high hardenability, and a fully martensitic microstructure was obtained from the dual furnace quenching and the standard 2 bar HPGQ processes, followed by standard deep freeze and tempering process. The coupons were deep Figures 6(a) and 6(b) compare the martensitic microstructure obtained from the two processes, and there is no noticeable difference. The hardness values were checked using coupons from both processes, and the average hardness values were approximately 49 HRC for both processes.

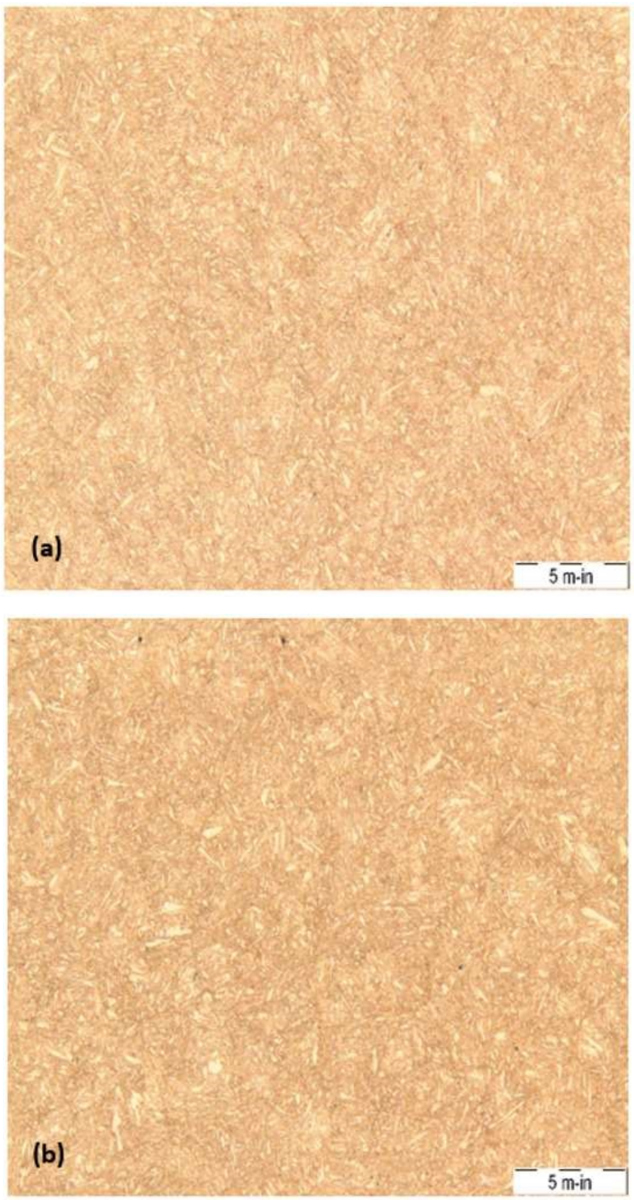



**Figure 6. Comparison of martensitic microstructures. (a) Standard 2bar HPGQ, and (b) Dual furnace quenching process.**

The mechanical properties obtained from standard, room temperature tensile experiments are compared in Table 1 for both processes. In Table 1, "STANDARD" refers to the standard 2 bar HPGQ process, and "TRIAL" refers to the dual furnace quenching process. "LONGITUDINAL" indicates tensile samples machined in the axial direction of the bar stock, and "TRANSVERSE" indicates the tensile samples machined in the transverse direction of the bar stock. There were no noticeable difference in the obtained tensile properties from the two processes.

**Table 1. Comparison of Mechanical Properties of C64 Steel Processed by Standard 2 Bar HPGQ and dual furnace quenching processes.**

| LONGITUDINAL (by HPGQ PROCESS) | | | | | | |
|---|---|---|---|---|---|---|
| SAMPLE ID | TENSILE STRENGTH | | YIELD STRENGTH | | ELONG. (%) | RA (%) |
| STANDARD | UNIT (ksi) | UNIT (MPa) | UNIT (ksi) | UNIT (MPa) | | |
| 01L | 236.0 | 1616.6 | 203.0 | 1390.6 | 17.00 | 71.00 |
| 02L | 236.0 | 1616.6 | 203.0 | 1390.6 | 17.00 | 71.00 |
| 03L | 235.0 | 1609.8 | 203.0 | 1390.6 | 17.00 | 71.00 |
| 04L | 236.0 | 1616.6 | 204.0 | 1397.4 | 16.00 | 71.00 |
| AVERAGE | **235.8** | **1614.9** | **203.3** | **1392.3** | **16.75** | **71.00** |
| LONGITUDINAL (by DUAL FURNACE QUENCHING) | | | | | | |
| TRIAL | UNIT (ksi) | UNIT (MPa) | UNIT (ksi) | UNIT (MPa) | | |
| 05L | 237.0 | 1623.5 | 204.0 | 1397.4 | 16.00 | 71.00 |
| 06L | 238.0 | 1630.3 | 202.0 | 1383.7 | 17.00 | 69.00 |
| 07L | 237.0 | 1623.5 | 203.0 | 1390.6 | 17.00 | 71.00 |
| 08L | 237.0 | 1623.5 | 203.0 | 1390.6 | 16.00 | 68.00 |
| AVERAGE | **237.3** | **1625.2** | **203.0** | **1390.6** | **16.50** | **69.75** |

| TRANSVERSE (by HPGQ PROCESS) | | | | | | |
|---|---|---|---|---|---|---|
| SAMPLE ID | TENSILE STRENGTH | | YIELD STRENGTH | | ELONG. (%) | RA (%) |
| STANDARD | UNIT (ksi) | UNIT (MPa) | UNIT (ksi) | UNIT (MPa) | | |
| 01T | 237.0 | 1623.5 | 204.0 | 1397.4 | 14.00 | 61.00 |
| 02T | 237.0 | 1623.5 | 204.0 | 1397.4 | 14.00 | 60.00 |
| 03T | 237.0 | 1623.5 | 205.0 | 1404.3 | 13.00 | 58.00 |
| 04T | 238.0 | 1630.3 | 204.0 | 1397.4 | 14.00 | 60.00 |
| AVERAGE | **237.3** | **1625.2** | **204.3** | **1399.1** | **13.75** | **59.75** |
| TRANSVERSE (by DUAL FURNACE QUENCHING) | | | | | | |
| TRIAL | UNIT (ksi) | UNIT (MPa) | UNIT (ksi) | UNIT (MPa) | | |
| 05T | 238.0 | 1630.3 | 205.0 | 1404.3 | 14.00 | 59.00 |
| 06T | 239.0 | 1637.2 | 205.0 | 1404.3 | 14.00 | 59.00 |
| 07T | 239.0 | 1637.2 | 205.0 | 1404.3 | 15.00 | 60.00 |
| 08T | 239.0 | 1637.2 | 205.0 | 1404.3 | 14.00 | 58.00 |
| AVERAGE | **238.8** | **1635.4** | **205.0** | **1404.3** | **14.25** | **59.00** |

Simplified single tooth bending coupons were processed using the standard HPGQ and the dual furnace quenching processes to evaluate their bending fatigue performance. The simplified tooth geometry was designed to represent a gear tooth from both the quench hardening and the bending stress aspects. Figure 7(a) shows the coupon geometry, with the size being approximately 10 mm x 15 mm x 50 mm. The bending load applied was normal to the tooth surface to avoid possible fretting. Figure 7(b) compares the obtained bending fatigue results using the coupons from the two processes. In Figure 7(b), the Y-axis is the maximum applied stress at the tooth fillet calculated using the finite element bending load model, with the assumption that there are no residual stresses from the heat treatment processes. Runout was considered to be 10 million cycles without failure, and a loading ratio of 0.1 was used for all the bending fatigue tests.

The fatigue results in Figure 7(b) show that the dual furnace quenching had slightly better performance than 2 bar HPGQ. The small difference may be due to the small stresses induced by cleaning and superfinishing, or the small surface roughness difference because they were processed separately. All the measured mechanical properties and bending fatigue from the dual furnace quenching are at least equivalent to those from the standard 2 bar HPGQ process, and it is believed that results from the DCGQ will be similar.

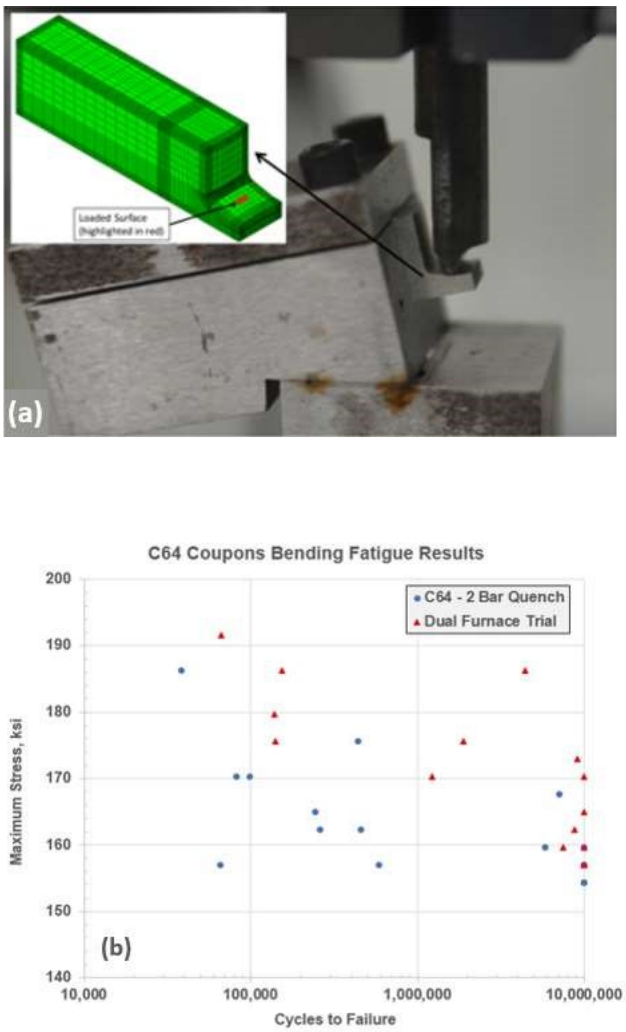



**Figure 7. Bending fatigue test of simplified tooth. (a) Bending fixture, and (b) Bending fatigue results.**

## DCGQ EQUIPMENT PROTOTYPE MANUFACTURING AND TRIAL RUNS

The DCGQ equipment prototype has been constructed and installed successfully. Figure 8(a) shows the Human Machine Interface (HMI) control panel of the equipment, and Figure 8(b) is a photograph showing the front door of the quenching chamber.

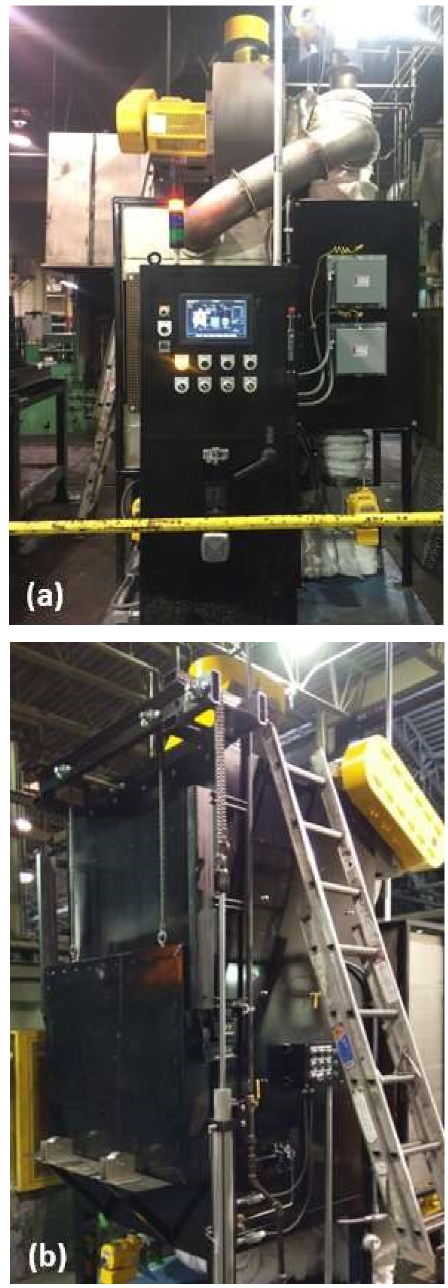



**Figure 8. DCGQ equipment prototype. (a) HMI control panel, and (b) Front door of quenching chamber.**

This equipment requires an external heating furnace for austenitizing the parts. For carburized parts, the parts will need to be carburized prior to the hardening process. During a quenching process, the ambient temperature of the chamber is controlled by the inlet gas temperature, and the inlet temperature is designed to follow a predefined schedule. A typical hardening treatment step using this DCGQ equipment is described below:

Step 1: Carburize parts, followed by slow cooling to room

Step 2: Reheat parts to austenitize in a heating furnace (stepped heating is preferred for reduced distortion)

Step 3: Transfer parts from the heating furnace to the DCGQ quenching chamber

Step 4: Fast cool the parts to a temperature slightly above the martensitic transformation start temperature

Step 5: Follow the DCGQ recipe to cool the parts to room temperature

Step 6: Deep freeze and temper parts following the standard procedure

Figure 9 shows a set of collected time-temperature curves from a trial run of the DCGQ equipment and the programmed recipe. The time-temperature curves in Figure 9 show the fidelity between the recipe set points and the measured inlet gas temperature introduced into the chamber. The chamber thermocouples show the uniformity around the basket of items being quenched, Lower1 and Lower2, as well as the overall uniformity in the chamber. The part temperatures were not recorded for this trial run.

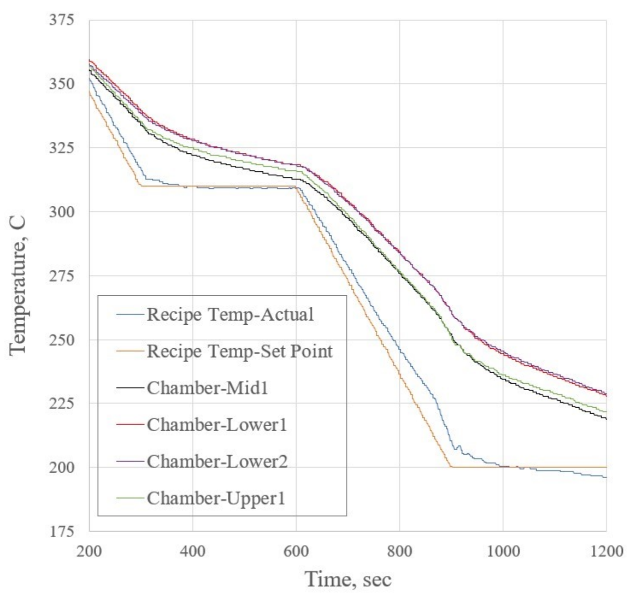



**Figure 9. Example of collected quenching chamber time-temperature data from a DCGQ trial run.**

Figure 10 is a set of temperature versus time curves for another trial run of the DCGQ unit with quenching a 4" diameter SS304 cylinder embedded with four thermocouples. Figure 10 shows the benefit of using a controlled cooling approach from the perspective of the component. The temperature difference between the surface and the core of the 4" cylinder probe is never more than 5° C during the martensite transformation range in this case. This would allow the martensite transformation to occur uniformly throughout the part, significantly reducing the shape change distortion.

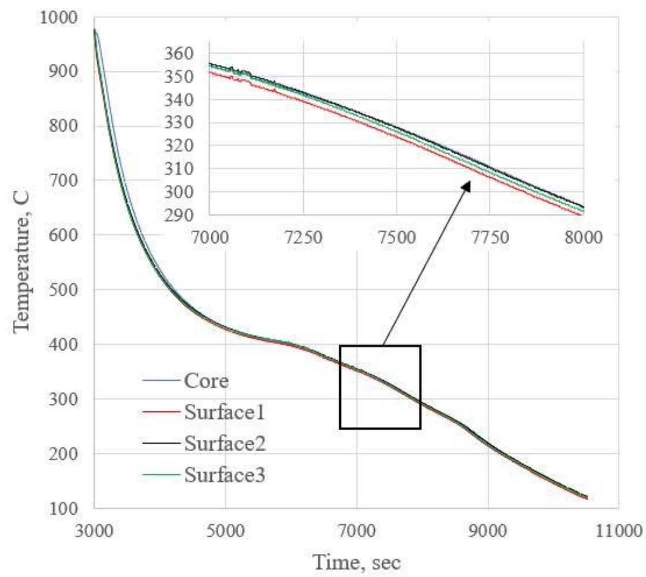



**Figure 10. Example of collected time-temperature data from a 4" cylindrical probe during a DCGQ run.**

As previously mentioned, mechanical property testing was performed using a dual furnace quenching approach, with the assumption that the cooling rate would mimic that of a DCGQ process. With the DCGQ prototype complete, a comparison was made between the cooling rate of the DCGQ process and the dual furnace process used for mechanical testing, as shown in Figure 11. The DCGQ curve in Figure 11 was from the thermocouple reading embedded in the 4" SS304 cylinder probe, and the Dural Furnace curve was from thermocouple reading embedded in a witness coupon.

As can be seen in Figure 11, the dual furnace cooling rate was actually slower than the DCGQ cooling rate. Therefore, it is expected that the mechanical and fatigue properties obtained using the DCGQ process should be equivalent to those obtained using a standard 2 bar quenching process.

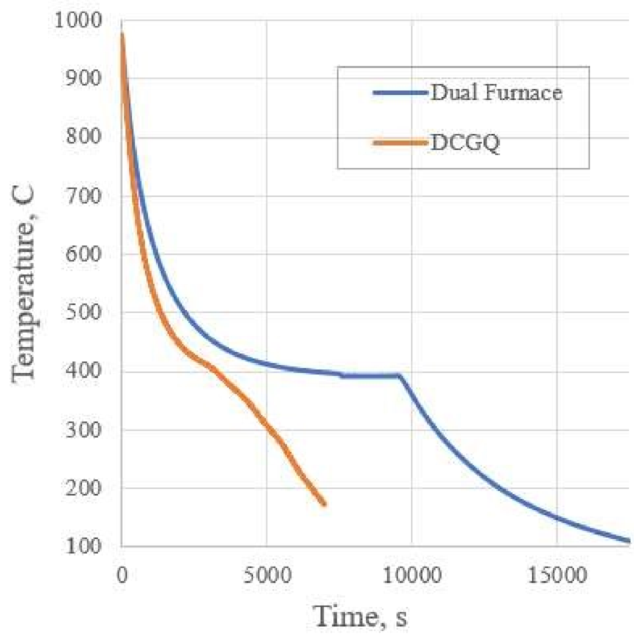



**Figure 11. Cooling rate comparison between dual furnace and DCGQ processes**

## CONCLUSIONS

Part distortion during high pressure gas quenching is a significant issue. A dual furnace quench process was developed to demonstrate that this distortion could be minimized by controlling the cooling process, while still achieving mechanical properties and bending fatigue performance equivalent to standard 2 bar HPGQ. Based upon the results of this dual furnace quench process, a prototype DCGQ unit was designed and fabricated. Experimental data from this DCGQ unit have shown very uniform quenching chamber temperature and flexible control of the chamber temperature by controlling the chamber inlet air temperature using a predefined recipe. The DCGQ concept can also be integrated with LPC and HPGQ equipment with nitrogen protective atmosphere and faster quenching rate. With a DCGQ equipment, the distortion can be greatly reduced, which will minimize or even eliminate any finish machining requirements after quench hardening.

**Authors contact:** Zhichao (Charlie) Li, Charlie.Li@Dante-Solutions.com

## ACKNOWLEDGMENTS

The authors wish to acknowledge the US Army ADD for their support of this work. Authors also wish to acknowledge Solar Atmosphere for heat treating the experimental coupons, Tensile Testing Metallurgical Laboratory for mechanical properties tests, and IMR Test Labs for the single tooth bending tests.

## REFERENCES

[1]Dowling, W., et al., "Development of a Carburizing and Quenching Simulation Tool: Program Overview," 2nd Int. Conference on Quenching and Control of Distortion, eds, G. Totten, et al., ASM Int., 1996.

[2]Li, Z., Ferguson, B. L., and Freborg, A., "Data Needs for Modeling Heat Treatment of Steel Parts", *Proceedings of Materials Science & Technology Conference*, 219-226, (2004)

[3]Li, Z. and Ferguson, L., "Gas Quenching Process Optimization to Minimize Distortion of a Thin-wall Ring Gear by Simulation", *HTM Journal of Heat Treatment and Materials*, Vol 68, No. 1, pp 35-41.

[4]Heuer, V., Loser, K., Leist, T., and Bolton, D., "Enhancing Control of Distortion through One Piece Flow – Heat Treatment", Fall Technical Meeting of American Gear Manufacturers Association, October 28-30, 2012, Dearborn, MI, USA, 2012.

[5]Lubben, T., Hoffmann, F.T., Mayr, P., Laumen, C., "The Uniformity of Cooling in High-Pressure Gas Quenching", Heat Treat. Metals, 27 (3) (2000), pp. 57–61.