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Advanced Distortion Control for Heat Treated Components

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Abstract

Material distortion is an undesired characteristic observed when a produced component requires a thermo-chemical heat treatment process followed by a rapid quench to obtain desired mechanical and metallurgical properties with uniform case depth and hardness profile. Due to the distortion taking place during this process, the manufacturer is faced with the costly choice of leaving excess material on a machined component before the heat treatment process, only to be removed after the heat treatment process by post heat treatment manufacturing methods. When steps are taken to reduce material distortion (prior to hard machining operations), manufacturers can significantly reduce costs and subsequently speed up the overall manufacturing process.

This paper will discuss the unique method of distortion control for heat treated and quenched components by use of a 4-Dimensional High-Pressure Gas Quench (4D Quench®) technique. This system has the ability to quench a single component without fixturing versus either a free quench or complex press quench approach. The 4D Quench® process results in components being individually quenched in an identical manner while having minimal distortion in relation to the green component. 4D Quench® systems are easily integrated into machining centers improving lead time and costs associated with traditional heat treatment processes.

Introduction

When one wishes to increase the hardness of steel, the steel must go through a metallurgical process which takes place when the steel is heated through its phase transformation into the austenitic range and then rapidly cooled causing the austenite to complete a phase transformation in to martensite. During the quenching process the component experiences a very large temperature gradient throughout its geometry and if the quench is not uniform, it leads to residual thermal stresses and non-uniform transformation of the microstructure. If the quenching application is not uniform, the component can experience a large deformation in relation to the pre-heat-treated geometry.

Manufacturers attempt numerous methods to reduce distortion after quenching as it is difficult and costly to remove excess material once the component has been hardened. Historically liquid quenching (due to its high heat transfer capabilities) has been the traditional quenching media used in the hardening process for centuries, however with liquid quenching comes high amounts of geometric distortion. High Pressure Gas Quenching (HPGQ) methods for hardening were developed in the 19th Century as alternative to liquid quenching and such have produced improved results in relation to geometric distortion. However traditional HPGQ methods fall short to that of liquid quenching when it comes to heat transfer capabilities.

2. Quenching

2.1. Liquid Quenching

When using a liquid quench technique for hardening, a component is heated to the required temperature(s) in a heating chamber separate from the quenching chamber. Liquid quenching chambers can be directly attached to the furnace (i.e. batch integral quench furnace), as a standalone chamber where a batch can be lowered or transferred to the quenching media (i.e. drop bottom furnace), or in a press quench where a singular component is quenched individually.

During liquid quenching, a part is exposed to three (3) stages; Vapor Stage, Boiling Stage, and Convection Stage (Fig 1.). The first stage (Vapor Stage), also known as the Leidenfrost phenomenon, generates a vapor blanket around the component thus insulating it from the quenching media. This stage occurs when the heat from the components surface is higher than the capability of the of the cooling media to remove such heat creating a vapor barrier surrounding the component. With the vapor barrier present it acts as an insulator and the cooling rate is considered relatively slow compared to the second stage (Boiling Stage) since heat transfer is being conducted through the vapor barrier. Note: during aqueous quenching, the vapor stage is not present.

The second stage (Boiling Stage) is where the highest heat removal takes place. This stage begins when the surface temperature of the component cools enough to allow the vapor barrier to collapse. The quenching media then begins to violently boil and heat starts to be removed from the component at a very high rate. During this stage, the component experiences its greatest amount of distortion.

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The third and final stage (Convection Stage) is slowest of the three stages. This stage begins when the temperature of the components surface is lowered to the boiling point of the quenching media and once this temperature is reached, the boiling stops. After boiling stops, cooling by conduction and convection takes over which is much slower than the previous stages.

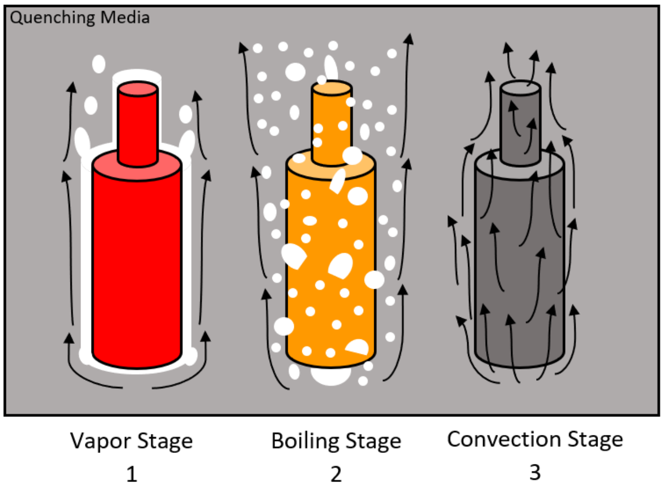

Fig. 1. *Stages of Liquid Quenching [1]*

Liquid quenching is one of industries fastest quenching methods and in most all cases can fully transform a component when quenched. Therefore, it is a widely used process in both atmospheric and vacuum furnaces. However due to the inconsistency in the various stages and challenge to control, liquid "free" quenching is one of the most distortion prone techniques being practiced. Additionally, when thermally processing in an atmospheric furnace, components will experience intergranular oxidation (IGO) due to the presence of oxygen within the furnace when at elevated temperatures. IGO is a negative phenomenon that occurs when oxygen atoms diffuse into the steel's surface reacting chemically with alloying elements. IGO when looked at under a microscope are tiny cracks (up to 0.007" deep) in a components surface [2]. If IGO is not removed initially by vacuum heat treatment processing, it must be removed by post heat treatment machining. IGO negatively impacts the wear resistance, fatigue resistance and hardness of the treated surface.

2.2. Press Quenching

A common method of distortion control during the quenching process is the press quench technique which does not employ batch quenching, rather it quenches one part at a time. Press Quenching is a special quenching technique designed to control quench process to minimize distortion caused when a part is rapidly quenched after the heating cycle. One of the critical aspects of press quenching is the design and construction of the special dies. These dies are built such that they mechanically align and retain a hot plasticized part with pressure as the die restricts the desired features from distorting when quenching through its phase transformation. Oil flow across the part surface is also important in achieving the desired hardness and microstructure, and such the dies must be produced to balance the need for die contact and proper oil flow over with the part. Common dimensions that require distortion control are runout, parallelism, concentricity, etc. and when press quenching is done in a proper manner, precise tolerances can be achieved, 0.001" – 0.002" [0.025 – 0.050mm], in relation to the pre heat treatment dimensions.

Description of a 4 stage Press Quench machine (Fig. 2.)
- Pos. 1 – Hot loading on lower die
- Pos. 2 – Upper die compression and oil flow
- Pos. 3 – Secondary (free) quench position
- Pos. 4 – Discharge tank with conveyer for final quench

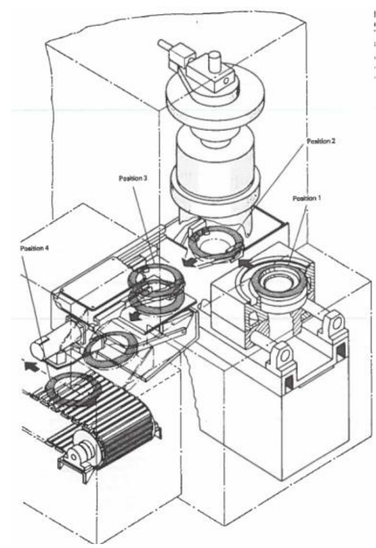

Fig. 2. *Illustration of a press quench machine, ©1991 ASM Handbook, Volume 4 [3]*

Press quenching offers very attractive results when it comes to distortion control however there are unattractive aspects of the process including safety concerns (handling of hot components), environmental (oil), washing (oil removal), etc. requiring special handling and equipment to quench a component after heat treatment. Subsequently if a component is not retained properly within the die, parts can be subject to severe distortion and even rupturing.

2.3. High-Pressure Gas Quenching (HPGQ)

An alternative to liquid quenching is that of High-Pressure Gas Quenching which is done in a vacuum furnace. In most cases, Nitrogen gas is the quenching media used in a HPGQ furnace, however in specialized situations, Hydrogen, Helium and Argon can be used as well. HPGQ is a much less aggressive quench practice to that of liquid quenching and due to HPGQ's kinetics, it offers less geometric distortion to the hardened component. HPGQ is becoming more and more common in

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industrial applications where it can offer numerous benefits as compared to liquid quenching. These advantages include:

- High quality (clean and bright) parts after heat treatment
- Very good process repeatability
- Environmental friendly
- No IGO
- Minimization of quench distortion
- Full automation of the thermal processes
- Easy process set up
- Full SCADA system
- Furnace flexibility with multiple processes
- Compact Design

Vacuum furnaces come in many different designs, from single chambers (vertical & horizontal), multi-chambers (batch & semi-continuous), and fully continuous (single-piece flow). Each design having a purpose to its individual construction. The most commonly used vacuum furnace design is a single chamber HPGQ furnace (Fig 3.) where the quenching gas is introduced into the heat chamber through nozzles positioned all around the heating chamber pointing towards the center if the working envelope (Fig 4.).

Fig. 3. *Horizontal Vacuum Furnace Installation*

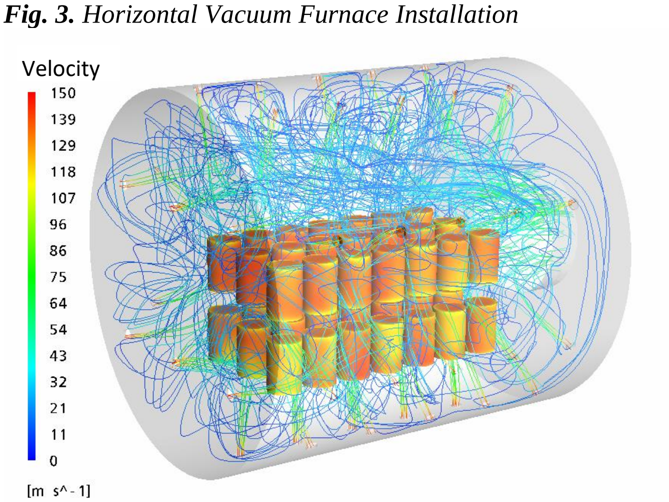

Fig. 4. *Horizontal Vacuum Furnace gas flow model*

With HPGQ significantly improving the quenching process results by decreasing the distortion rate. Gas quenching is a single-phase process and a more uniform process with respect to a single part. Moreover, quenching rates can be regulated freely by a change of gas pressure (density) and velocity (fan rotation), thereby making the quenching process - controllable. Modern HPGQ systems with nitrogen or helium operating under 25 bar abs. pressure are reaching the equivalent to oil quenching. As an added benefit, gas quenching eliminates the process of washing making it a much more environmentally friendly process. They are flexible, can be switched on and off at any time, and only require approximately one (1) hour to become production ready. Additionally, they do not require any atmosphere stabilization and the process parameters can be changed virtually instantaneously.

2. Batch Quenching

In traditional hardening systems, parts are configured and processed in batches on special fixtures (Fig. 5.) and undergo the hardening process in such a configuration. This means that each part in a batch is affected by the process conditions in a unique manner, based on its position within the batch. Each part is affected differently regarding the heating rate, composition of the process atmosphere, and intensity and direction of the cooling medium. Parts in the outer layers versus than those in the center of the batch are heated more quickly, to a different temperature, different case (as in carburizing) and they are quenched more intensely. The result is that parts inside the batch have different physical and metallurgical properties than those on the outside of the batch, e.g., surface and core hardness, microstructure, and especially the effective case depth [4], [5]. Since batch processing is the most accepted form of thermal processing, industry requirements have been forced into accepting case depth variations up to +/-30%.

Fig. 5. *Typical Batch Configuration*

A critical summary of batch 2D quenching (especially oil quenching) shows that it is an uncontrolled and non-uniform process, producing great deformations within each part and little consistency within the batch. Distortions have to be removed finally by final machining or others correction method. Batch processing also has other quality, material handling and cost pitfalls. When we talk about monitoring and reporting of traditional case hardening process's, the data

Heat Treat 2019: Proceedings of the
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October 15–17, 2019, Detroit, Michigan, USA

represents the entire batch of components and not the individual piece. Because of this process flaw it makes it difficult, or even impossible, to introduce and/or implement more higher quality standards. These varying parameters have a negative effect on the component's quality and repeatability when thermally processed. Depending on the type of equipment used, batch processing can have varying tolerances as much as 0.120" [3 mm].

As a separate issue, the intensity and uniformity of components quenched in a batch is also inconsistent. Intensity of quenching determines the hardness of the core and effective case depth (ECD). Uniformity determines the dispersion of quenching parameters across the components and fixturing within the batch. Most importantly about intensity and uniformity is the amount of size changes due to distortion from quenching. Regardless of the quenching platform employed, liquid or gas, all batch quenching has one important common feature, the single-direction cooling flow, in other words a 2D Quench (Fig. 6.).

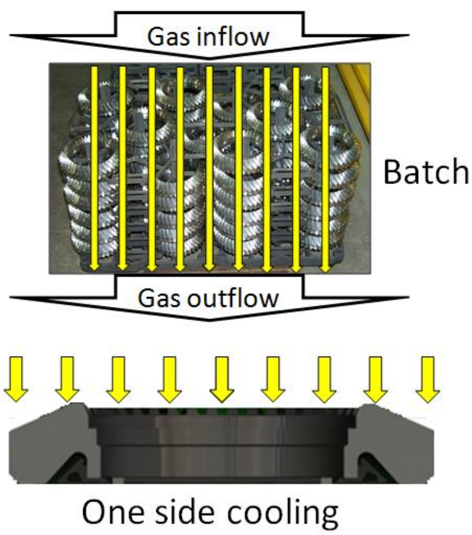

Fig. 6. *2D cooling gas flow illustration on a load and part*

This means that an individual part is affected in one specific direction by the cooling media flow. Flow directions can include top to bottom, bottom to top, or from side to side, etc. A consequence of 2D quenching is that the part cooling rate is not uniform in different places on the part (Fig. 7). The lack of uniformity in quenching results in temperature gradients within each part which leads to high thermal stresses, non-uniform transformation of the microstructure and dimensional distortion.

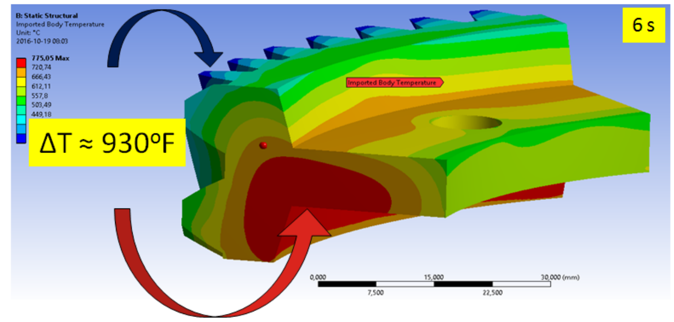

Fig. 7. *Temperature gradient in 6 sec. under 20 Bar N2 top to bottom gas flow*

3. 4D High Pressure Gas Quench

3.1. 4D Quench®

4D Quench® is a new process that allows for significant improvements to the quenching process with the main focus on reduction of distortion and to provide process repeatability. Distortion reduction is achieved mainly from the use of a high-pressure gas quenching system installed in the quenching/unloading chamber (Fig. 7.). The 4D Quench® platform utilizes a proprietary cooling manifold and chamber (Fig. 8.) arrangement that surrounds the part during the quenching process. This approach ensures a that there is a uniform flow of cooling gas across the part geometry (top, bottom, and side). When talking about top, bottom, and side quenching, this is referred to as "3D" cooling.

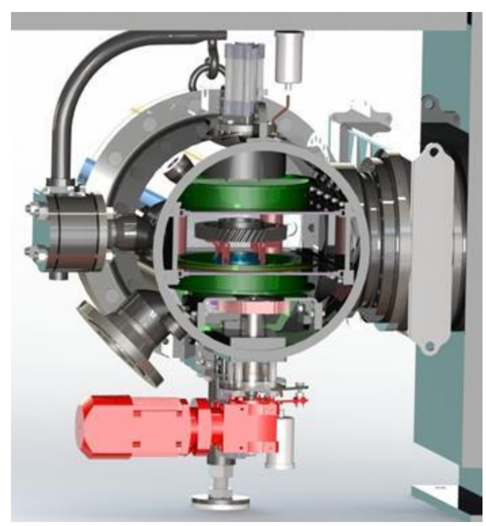

Fig. 7. *4D Quench®/Unloading Chamber*

In order to achieve the 4th Dimension when quenching, a component is placed in the quenching chamber, the proprietary cooling manifold surrounds the part and finally the support table rotates the component while nitrogen cooling gas flows over the part. Adding both the 3D quenching approach with part rotation, we give birth to 4D quenching which has the ability to further enhance quench uniformity. With 4D HPQG, it also allows for the best possible quench uniformity to be utilized. Also, and most importantly, since the cooling nozzles can be adjusted to fit the component's precise size and geometry, quenching can be fully optimized and distortion significantly reduced.

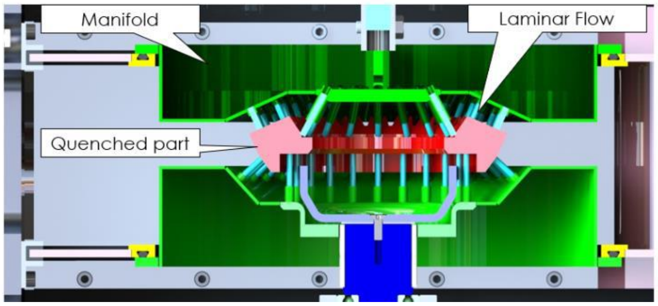

Fig. 8. *Quenching gas flow in the 4D Quench® Chamber*

3.1. 4D Quench® Power

When discussing quenching, furnaces systems will use various quenching processes/media to achieve the desired metallurgical properties. Based on a materials ability or should I say "in-ability" to be hardened, more aggressive cooling rates may be needed to reach the required hardness as required for the components end use. The quenching chart (Fig 9.) shows the three (3) main types of quenching oil (Fast, Medium and Slow) in relation to the various quenching gasses (N2, He, H2) used in batch thermal processing. When we look first at the quench oils, the general heat transfer coefficient (or quenching capability) range across all three oil types is ~1000 – 2500 $\alpha[W/m^2K]$.

The chart then shows the relationship between the three types of gas and how they perform when the pressure increases in the chamber. The vertical dashed lines represent 2 categories in which vacuum HPGQ furnaces are generally constructed. The dashed line noted at the 14 Bar mark represents a typical single chamber batch HPGQ furnace and the dashed line noted at the 24 Bar mark is a typical multi-chamber batch HPGQ furnace. Multi-chamber simply means it has a dedicated heating and quenching chamber where the thermally soaked hot zone is not quenched, thus allowing a multi-chamber HPGQ furnace to perform better than that of a single chamber furnace. However, a downside to the multi-chamber batch HPGQ furnace is a more complex and costlier to manufacture than that of a batch HPGQ furnace.

When comparing N2 batch HPGQ vs. oil quench, whereas N2 being the most common gas quenching media used in HPGQ, it just begins to become as strong as oil when entering the 20-24 Bar ranges. He and H2 round out the other 2 gasses which both perform better than N2. However, the disadvantages are that He is very costly to purchase and requires expensive reclaiming systems while H2 has its inherent safety regulations and concerns which prevent it from being used in today's quenching processes. So where do we go from here? As you can see, 4D Quench® when only using 9 Bar of N2 quenching gas, has capabilities that fall into the Fast Oil quenching range.

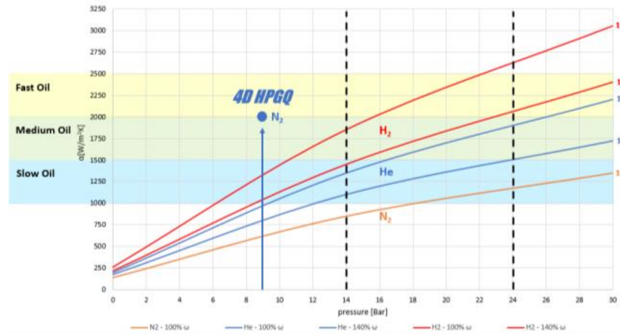

Fig. 9. – *4D Quench®, Batch HPGQ, & Oil - Quench Speed Relationship*

3.2. 4D Quench® Optimization

Optimization of the quenching process within the 4D Quench® chamber can be performed in multiple ways with the adjustment of one or more of its features (Table 1.).

Feature	Description
Quench Pressure	1 to 10 Bar abs. gas pressure
Gas Velocity	Cooling blower RPM control
Gas Manifold	Distributes quenching gas evenly across the component
Table Rotation	ON or OFF with RPM and directional adjustment
Table Oscillation	Angle adjustment
Time Dependent Gas Flow	Controlled via time in seconds

Table. 1. *4D Quench® features*

With the simple adjustment of these parameters, a user now has the complete flexibility to optimize the quenching process to reduce distortion, maintain part to part repeatability and achieve precise accuracy after a component is thermally processed.

3.3. Uniform Quenching

To further illustrate the uniform quenching capability of 4D Quench®, the system has the ability to video record the entire quench process via a small camera on the quenching chamber. As you can see in the snapshots from the video (Fig. 10.), show the quenching uniformity to be very even and rapid. This example has the part cooled from its "red-hot" color @ 1550ºF [845ºC] to its black color ~800ºF [425ºC] in 15 seconds.

With all of these features that are able to be adjusted, this means that the 4D Quench® material cooling system is a perfect tool to give unlimited possibilities to form and control the cooling process, allowing a user to establish the optimum parameters required for a component to be quenched.

Heat Treat 2019: Proceedings of the
30th ASM Heat Treating Society Conference
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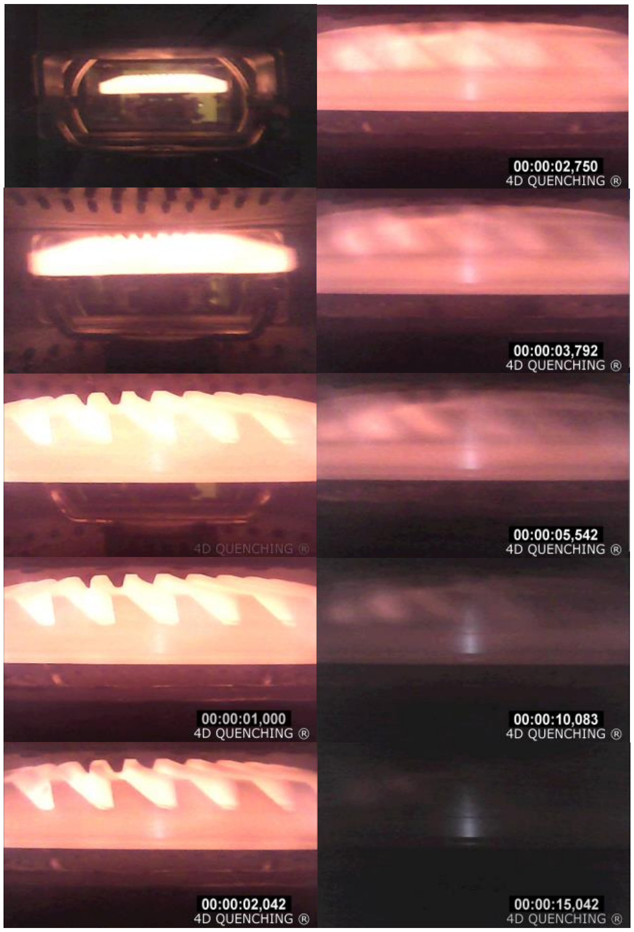

Fig. 10. *4D Quench® live quenching images*

4. Process Example

4.1. Coupling Sleeve Case Study

Couplings sleeves are a critical component to a gearing system (Fig 11.). Due to their complex geometry, they are prone to high levels of geometric distortion during following the heat treatment process. Several reasons for a coupling sleeve to distort is because of its thin wall construction and gear tooth geometry.

Fig. 11 *Coupling Sleeve Trial Component Image.*

In the following case study 20 Coupling Sleeves were case hardened by Low Pressure Carburizing and 4D Quench® in a SECO/WARWICK single piece flow UniCase Master® vacuum furnace (Fig 12.) followed by the tempering process. To prove 4D Quench's® ability to reduce component distortion after heat treatment; the components were dimensionally inspected by a Coordinate Measuring Machine (CMM) Global Performance 5.7.5. with a measuring accuracy of 2 μm (0.00008"). Dimensional inspections were taken prior to the heat treatment process labeled "Green parts" and following the case hardened heat treatment process labeled "Case hardened parts". Further solidification of the trial's precedence, separate critical measurements were taken which include; Radial runout, Axial runout, Total pitch deviation, Total profile deviation and Total helix deviation (Fig 13.1., 13.2., 13.3., 13.4., 13.5.).

Fig.12. *UniCase Master® Complete HT System*

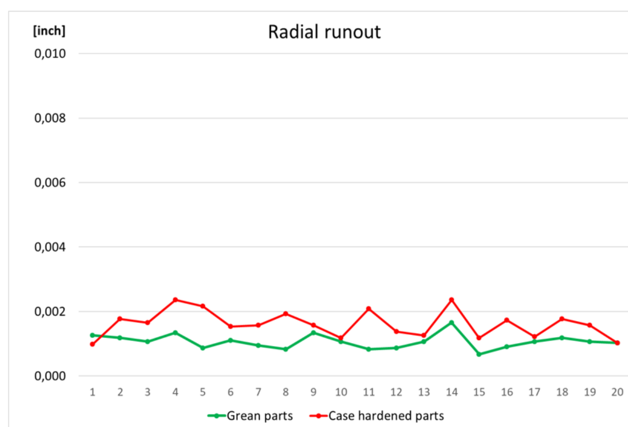

Fig. 13.1.*, Coupling Sleeve Radial Runout Inspection Chart*

Heat Treat 2019: Proceedings of the
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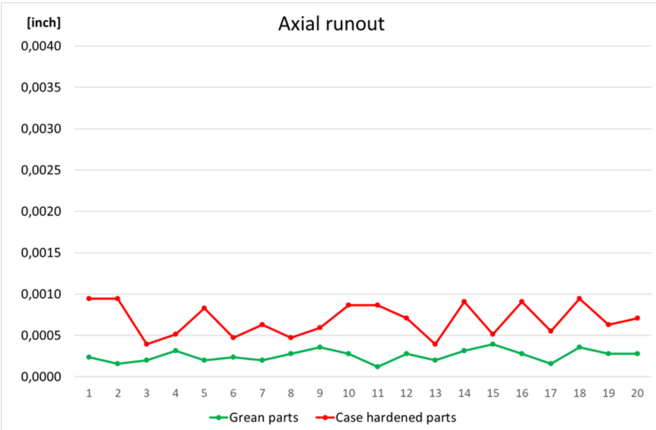

***Fig. 13.2.**, Coupling Sleeve Radial Runout Inspection Chart*

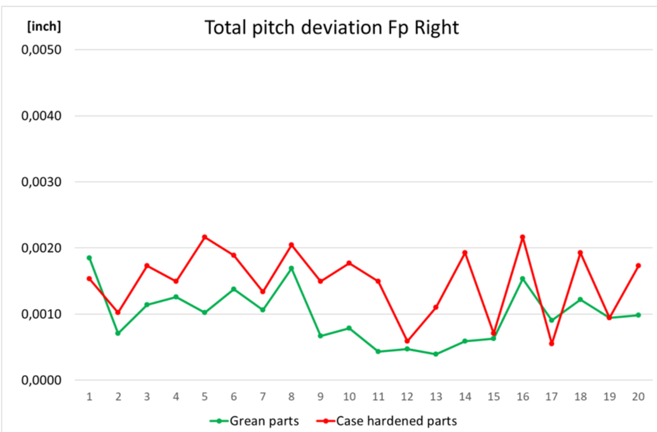

***Fig. 12.3.**, Coupling Sleeve Total Pitch Deviation Inspection Chart*

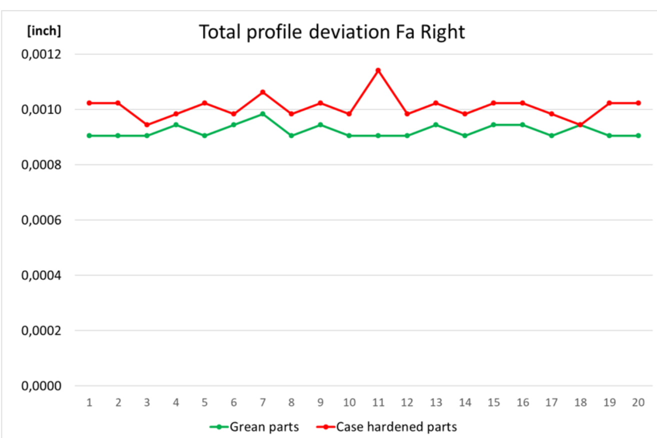

***Fig. 12.4.**, Coupling Sleeve Total Profile Deviation Inspection Chart*

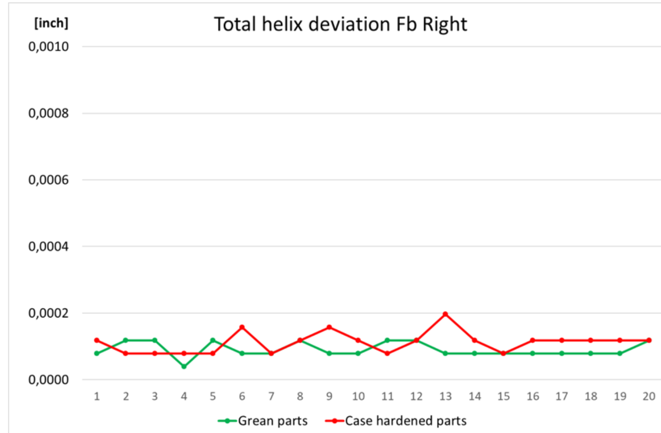

***Fig. 12.5.**, Coupling Sleeve Total Helix Deviation Inspection Chart*

Upon the conclusion of this trial you can see that coupling sleeves post heat treatment geometry experienced minimal deviation to that of its green pre heat treatment condition. Most dimensional features experienced less than 0.001” [0.025mm] of difference from the green condition. Under this 4D Quench® trial, it has been proven that the coupling sleeve’s AGMA Quality level has achieved a >12 Class proving the system’s ability to out-perform any other quenching method.

To put this into perspective, a typical batch heat treatment processing this same coupling sleeve can experience upwards of 0.020” to 0.030” [0.5 to 0.75mm] in dimensional deviations which leaves a manufacturer the difficult choice to spend much more time and cost to remove these huge deviations or even scrap the part all together.

5. Conclusion

Current and best available solutions for the hardening process, both batch and continuous, fail to meet current and future expectations for high-volume gear manufacturers and other high production manufactures in terms of quality, repeatability, flexibility, integration of production, environmental-friendliness, and costs, mainly because parts are arranged as batches.

The 4D Quench® System has been developed to be a real single-piece flow vacuum hardening system which eliminates the shortcomings of the current technologies. It meets the current and future requirements of high-volume gear manufacturers and has the following features:

- Repeated precision in process results
- Reduced quenching distortion due to 4D Quench®
- Integration into continuous production lines – lean manufacturing
- Achieved high-volume productivity for gear and bearing manufacturers as well as other industries
- Designed to be flexible with fine-tuned process parameters and throughput
- Monitored production with 100% traceability and reporting of individual parts

- Elimination of fixtures (cost, energy) and batch material handling logistics
- Elimination of quench oils, washers, washing fluids
- Controlled safety with avoidance to the potential for fires and explosion hazards
- Clean process, no effect on the environment
- Applying cutting edge HPGQ technologies

4D Quench® allows for significant improvements in the quenching process, specifically the reduction of distortion. The systems properties and advantages have elevated the hardening process to the next level and can pave the way to development of the increasingly stringent quality and production requirements of high-volume gear and bearing manufacturers

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