Advances in Quenching

A Discussion of Present and Future Technologies

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Management Summary

Heat treating and quenching are arguably the most critical operations in the manufacture of gears. It is these processes that provide a gear with the proper mechanical and wear properties to withstand high contact stresses and have high longevity. Unfortunately, heat treating and quenching are often the least understood in the manufacturing stream. Parts are often distorted or stained after heat treatment. It is often the "black hole" on which all the ills of the manufacturing process are blamed.

It is the purpose of this article to examine the causes of distortion during the heat treatment and quenching of gears and provide some insight into proper action to correct distortion and high residual stresses during quenching.

Introduction

Regardless of the product, it is likely that it is heat-treated and quenched. Engine components are heat treated for wear and durability. Aircraft components are heat treated for strength and fracture toughness. Even bicycle frames are heat treated for strength, lightness and durability. Furnaces are specially designed to heat treat products quickly and cost-effectively. To meet these needs, it is necessary to expand the knowledge of heat treating and quenching to consistently produce a quality product, capable of being manufactured in a cost-effective manner.

In metallurgy, the definition of quenching is "the controlled extraction of heat." The most important word in this definition is "controlled." The quenchant is any medium that extracts heat from the part. The quenchant can be a liquid, solid, or gas.

When a hot component comes in contact with a liquid quenchant, there are normally three stages of quenching (see Fig. 1):

- Vapor Stage (Stage A or Vapor Blanket Stage)
- Boiling Stage (Stage B or Nucleate Boiling Stage)
- Convection Stage (Stage C)

The vapor stage is encountered when the surface of the heated component first comes in contact with the liquid quenchant. The component becomes surrounded with a blanket of vapor.

In this stage, heat transfer is very slow and occurs primarily by radiation through the vapor blanket. Some conduction also occurs through the vapor phase. This blanket is very stable, and its removal can only be enhanced by agitation or speed-improving additives. This stage is responsible for many of the surface soft spots encountered in quenching. High-pressure sprays and strong agitation eliminate this stage. If the surface spots are allowed to persist, undesirable microconstituents can form.

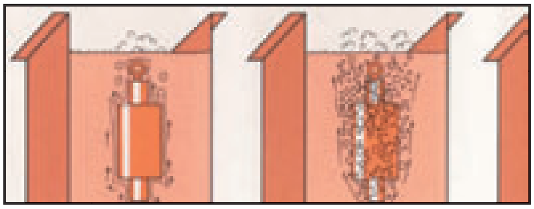

Figure 1—Schematic representation of the three stages of quenching for normal quench oil: 1) Left—vapor barrier formation; 2) Center—vapor barrier collapse and nucleate boiling; 3) Right—convection.

The second stage encountered in quenching is the boiling stage. This is where the vapor stage starts to collapse and all liquid in contact with the component surface erupts into boiling bubbles. This is the fastest stage of quenching. The high heat extraction rates are due to heat being carried away from the hot surface and transferring it further into the liquid quenchant, which allows cooled liquid to replace it at the surface. In many quenchants, additives have been utilized to enhance the maximum cooling rates obtained by a given fluid. The boiling stage stops when the temperature of the component's surface falls below the boiling point of the liquid. For many distortion-prone components, high-boiling-temperature oils or liquid salts are used if the media is fast enough to harden the steel, but both of these quenchants have relatively little use in induction hardening.

The final stage of quenching is the convection stage. This occurs when the component has reached a point below that of the quenchant's

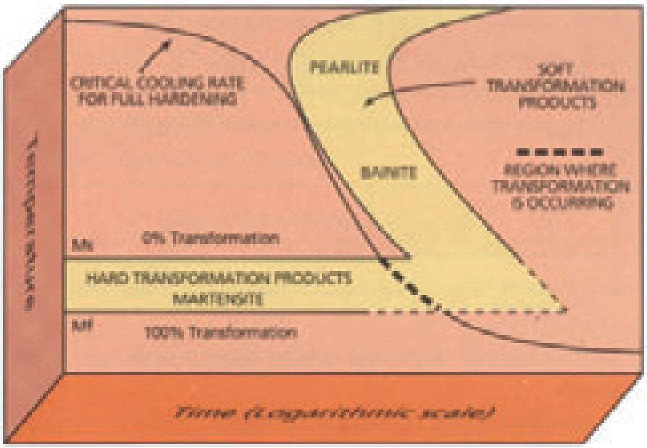

Figure 2—A time-temperature-transformation (TTT) diagram illustrating the critical cooling rate for complete martensitic transformation.

boiling temperature. Heat is removed by convection. It is controlled by the quenchant's specific heat and thermal conductivity, and the temperature differential between the component's temperature and that of the quenchant. The convection stage is usually the lowest of the three. Typically, it is this stage where most distortion occurs.

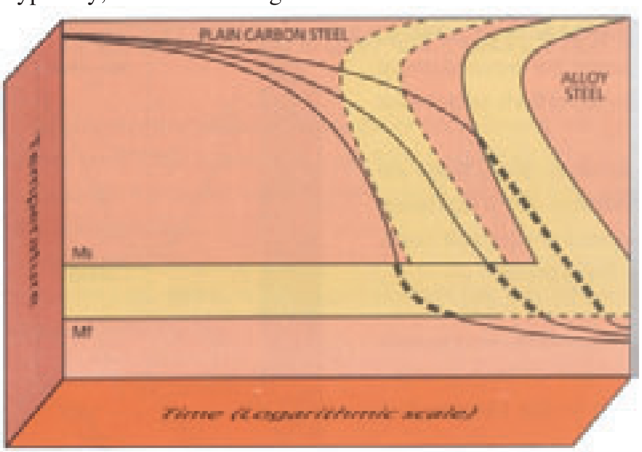

Figure 3—The effect of alloy content on steel hardenability.

Obtaining desired properties and achieving low distortion is usually a balancing act. Often, optimal properties are obtained at the expense of high residual stresses or high distortion. Low distortion or low residual stresses are usually obtained at a sacrifice in properties. Therefore, the optimum quench rate is one where properties are just met. This usually provides the minimum distortion.

Table 1—Martensite Start Transformation Temperature (M_s) as a Function of Carbon Content.

Carbon Content M_s	Temperature
0.2%	430°C
0.4%	360°C
1.0%	250°C

To achieve proper strength and toughness, it is necessary to convert austenite to martensite, which is then altered to form the proper tempered martensitic microstructure. To achieve this conversion of austenite to martensite, a rapid quench rate is required. This quench rate must be fast enough to avoid the formation of upper transformation products, like bainite and pearlite, and convert all austenite to martensite. This critical quench rate just misses the "knee" of the time-temperature-transformation (TTT) curve (Fig. 2). The rate of the critical quench rate is dependent on the steel chemistry.

In practice, when a steel component is quenched, the surface cools much more rapidly than the center. This means that the surface could cool at the critical rate and be fully hardened, but the center cools more slowly and forms a soft pearlitic or bainitic microstructure.

Hardenability is the ability of steel to through-harden. It is not the ability of the steel to harden. In a sense, it is a measure of the critical cooling rate on the TTT curve.

Increasing the hardenability of steel is accomplished by increasing its alloying content. Manganese, chromium and molybdenum are all effective alloying elements that increase a steel's hardenability. These elements cause a delay in transformation by shifting the transformation curve to the right. This reduces the critical cooling rate for martensitic transformation (Fig. 3). However, alloying elements may be expensive and not always beneficial to other processes, such as machining or forging.

Increasing the alloying content is not a simple panacea. Increasing the carbon and alloying content can also have deleterious effects by lowering the martensite-start transformation temperature (M_s). Increasing the carbon content, while shifting the TTT curve to the right, significantly lowers the M_s temperature (Table 1). Alloying elements also increase the "effective carbon" content according to the following formula (Ref.1):

$$C_{eq} = C + Mn/5 + Mo/5 + Cr/10 + Ni/10$$

Cracking and distortion increase along with the "effective carbon" content. Alloys become prone to distortion and cracking as the "effective carbon" content exceeds 0.52%. This tendency is decreased by the proper application of quenchants. A quenchant is used that is fast enough to achieve the desired properties, but slow enough that cracking or excessive distortion will not occur.

The cooling characteristics of a quenchant can be measured using probes instrumented with thermocouples. Various techniques have been used, including both cylindrical and spherical probes manufactured from a variety of metals, including stainless steel, silver and nickel alloys. One of the most widely used and accepted methods is based upon the use of a 12.5 mm diameter cylindrical probe manufactured from Inconel 600® alloy, as specified by the Wolfson Heat Treatment Center (WHTC) Engineering Group, recommended by the International Federation for Heat Treatment (IFHT) and adopted by the International Standards Organization (ISO 9950).

Results obtained by the different test methods vary depending upon the material, geometry and surface condition of the probe. Cooling curves produced in this way illustrate well the three stages of quenching and demonstrate the influence that factors such as agitation, quenchant temperature, contamination and degradation have upon quenching performance.

The cooling characteristics can either be shown as a graph of temperature against time or as a graph of temperature against cooling rate, as shown in Figure 4 for both normal speed and high speed quenching oils.

The duration of the vapor phase and the temperature at which the maximum cooling rate occurs have a critical influence on the ability of the steel to harden fully. The rate of cooling in the convection phase is also important since it is generally within this temperature range that martensitic transformation occurs. Therefore, it can influence residual stress, distortion and cracking.

However, cooling curves produced under laboratory conditions must be interpreted carefully and should not be considered in isolation. Results on used quenchants should be compared with reference curves for the same fluid.

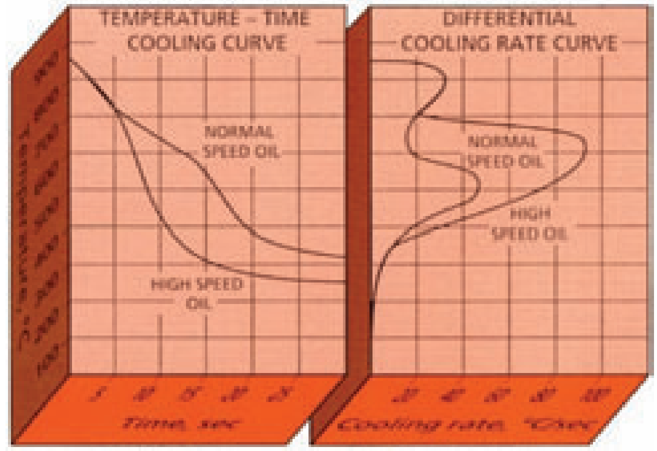

Figure 4—Temperature-time cooling curve and the differential cooling rate curve.

Oil Quenchants

It is not known how long oils have been used in the hardening of ferrous alloys. Many types of oils have been used, including vegetable, fish and animal oils, such as sperm whale oil. The first petroleum-based quenching oils were developed around 1880 by E.F. Houghton in Philadelphia. Since that time, much advancement has been made in the development of quenching oils to provide highly specialized products for specific applications.

A wide range of quenching characteristics can be obtained through careful formulation and blending. High quality quenching oils are formulated from refined base stocks of high thermal stability. Selected wetting agents and accelerators are added to achieve specific quenching characteristics. Complex antioxidant packages are included to maintain performance for long periods of continued use, particularly at elevated temperatures. Emulsifiers may be added to enable easy cleaning after quenching.

Petroleum Oil-Based Quenchants

Petroleum-based quench oils can be divided into several categories, depending on the operational requirements. These requirements include quenching speed, operating temperatures and ease of removal.

The quenching speed is important because it influences the hardness and the depth of hardening. This is probably the most common method of classifying quench oils. They can be classified as normal, medium or high speed.

Normal speed quench oils have relatively low rates of heat extraction and are used in applications where the material being quenched has a high hardenability. Highly alloyed steels, such as AISI 4340, or tool steels are typical examples of steels quenched in normal speed oils.

Medium speed quench oils provide intermediate quenching characteristics and are widely used for medium to high hardenability applications where dependable, consistent metallurgical properties are required.

High speed quench oils are used for applications such as low hardenability alloys, carburized and carbonitrided components, or large cross-sections of medium hardenability steels where high rates of cooling are required to ensure maximum mechanical properties. A comparison of the quenching speeds of the different types of quench oil is shown in Figure 5.

Marquenching oils are a special case where the part is quenched at elevated temperature, typically 100–200ºC. The workpiece is held in the quenchant until temperature equilibrium is established throughout the section, and then air-cooled to ambient temperature.

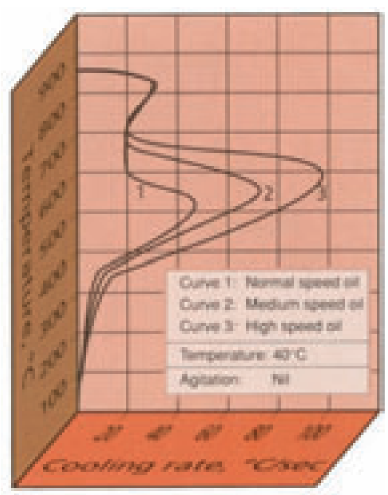

Figure 5—Cooling curves for normal, medium and high speed quenching oils.

During marquenching, components are quenched to an intermediate temperature close to the M_s temperature and held at this level. This eliminates the temperature gradients across the surface. Consequently, during subsequent slow cooling after removal from the hot oil, transformation to martensite occurs uniformly throughout the section. This minimizes the generation of internal stresses and reduces distortion.

Since marquenching oils are used at relatively high temperatures, their formulation and physical properties are different from cold quenching oils. They are formulated from very carefully selected base stocks with high oxidation resistance and thermal stability. They have high flash points and viscosities and contain complex antioxidant packages to provide long life. Selection of the marquenching oil is based on the operating temperature and quenching characteristics. A minimum of 50ºC should be maintained between the operating temperature of the oil and its flash point.

However, the source of distortion and residual stresses is not limited to the martensite start temperature, the oil used, or the alloy content. There are a number of sources of residual stresses, and not all of them are heat treating-related. A schematic of some causes of distortion and residual stresses is illustrated in Figure 6.

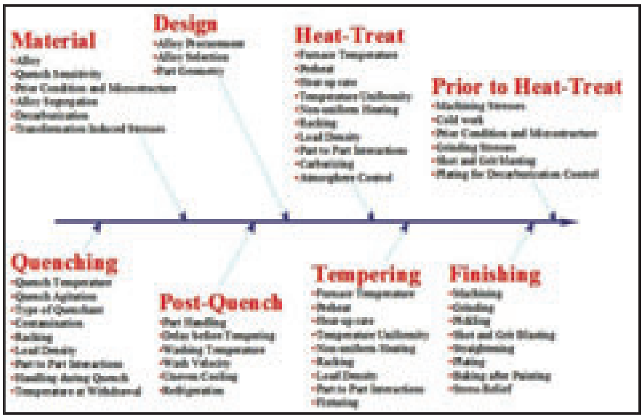

Figure 6—Fishbone diagram of the potential causes of residual stresses and distortion.

Distortion and Residual Stresses

By far the largest source of problems for heat treaters is distortion of parts after heat treatment. Distortion causes excessive noise in the gear drive train and potentially early failure due to high residual stresses. It can be seen in Figure 6 that many of the sources of residual stress and distortion occur before heat treatment and quenching, yet it is often the heat treater that gets the blame for a distorted part.

Material. The alloy chosen can play an important role in how sensitive a part is to distortion during quenching. If the equivalent carbon C_{eq} is greater than 0.52%, it is prone to high residual stresses from transformation stresses and cracking (Ref. 1). If it has low hardenability, fast quench rates are required to meet properties. This can also cause residual stresses because of the development of thermal gradients during quenching that can cause some areas to transform to martensite earlier than other areas. Segregation in the raw material can cause local areas of high hardenability, which can also cause localized early transformation to martensite, creating metallurgical notches that are prone to cracking.

Design. Often the design of a part is responsible for cracking or distortion. For instance, if sharp radii are used or there is little transition between thick and thin sections, a high level of constraint forms. This can result in distortion or cracking. It is always a good idea to use generous transitions between sections and minimize the use of thick and thin sections.

Prior to heat treatment. Many processes, such as forging and casting, create large residual stresses during the formation of the green shape. This is due to the elevated temperatures, the non-uniform deformation, and the subsequent non-uniform cooling. Different microstructures are formed. This will cause non-uniform response to heat treatment. Also, because of the non-uniform deformation that occurs during forging, significant residual stresses are formed. To relieve these stresses, it is always recommended to normalize the forgings prior to machining. This serves two purposes—first to provide a semi-uniform microstructure (ferrite and pearlite) for machining and secondly to reduce the residual stresses occurring during forging.

One practice that is always recommended, but is rarely implemented, is to spheroidize anneal the parts after normalizing. This practice causes the carbides in the pearlite to form uniformly distributed carbide spheres. This makes a steel much easier to machine, and it forms chips readily. The material is softer, more uniform, and has a better surface finish. Tool life is improved. As an added benefit, response to heat treatment is also much more uniform and consistent. Typical spheroidizing cycles are long (10+ hours) and at elevated temperatures (1,250–1,325°F). Because of the time involved and the cost of furnace time, this valuable step is often skipped.

In the case of castings, the solidification rate is non-uniform, meaning that there will be localized segregation and that the concentration of alloying elements will not be uniform throughout the part. During heat treatment, this non-uniformity will cause different hardness responses and variable distortion. Often the castings are homogenized to reduce the local chemical gradients. It is also recommended that a normalization anneal is performed to increase homogeneity of the microstructure.

Many of the processes prior to heat treatment involve the removal of material. These can include grinding, broaching, turning, and other machining operations. Because of the speed and feed rates at which these operations must operate to be profitable, a large amount of residual stresses can be created in the part. The stresses will be relieved during heat treatment, resulting in part distortion. To minimize the formation of residual stresses, it is often necessary to turn the part over several times during the machining operation. It is also often necessary to include several stress relief operations during the machining operations. The amount of residual stresses created in a shop is highly dependent on its various practices. This includes tool sharpening frequency, feeds and speeds, the coolant used, geometry of the tool, etc.

Heat treatment. Parts containing residual stresses prior to heat treatment will relieve those stresses during heat treatment. The relaxation of these stresses will cause distortion as the part finds a stress-free equilibrium. Heat-up rates in the furnace can also cause distortion, as thermal gradients are formed and the thinner sections reach temperature quicker. There will be differential thermal expansion, which can cause sizable thermal strains to be developed within the part. If these thermal strains are large enough, then plastic deformation and distortion can occur. The use of a preheat stage to allow thicker sections to "catch-up" to the thinner section will reduce distortion. The same thing can occur if the furnace has non-uniform temperature within the work zone.

Racking of parts is an extremely important part of the heat-treating process. Proper racking minimizes part-to-part interactions and allows heat to reach all parts. It further allows the quenchant to evenly extract the heat from parts in a uniform fashion.

The role the atmosphere plays is often overlooked in the control of distortion and residual stresses. Most gears are carburized to achieve a hard wearing surface. In non-wear critical areas, carburizing is not needed. These regions are plated or coated with a carburizing stop-off to prevent the diffusion of carbon into the steel. As steel transforms from austenite to martensite, there is a volumetric expansion that increases as the carbon content increases:

$$\Delta V/V \text{ x } 100 = 1.68(100 - V_c - V_a) + V_a(2.21C - 4.64)$$

where ΔV is the change in volume; V_c and V_a are the volume fractions of carbon and austenite; and C is the concentration of carbon in the steel (Ref. 2). Typically this amount is between 3–5% for carburized steel. This volume change will cause differential transformational strains, which may cause distortion. While these strains may not cause distortion to occur immediately after heat treat, distortion can appear immediately after any subsequent machining steps, as the part tries to achieve a new static equilibrium. These residual stresses can also manifest themselves by shortened fatigue life.

Proper atmosphere control is important. Excessive soot can be carried into the quench oil, creating dirty parts, and shortening the life of the quench oil. Proper atmosphere control can also reduce the amount of retained austenite, which can also cause residual stresses and distortion.

Quenching. From Figure 6, it can be seen that there are many sources of residual stress and distortion. In quenching, the primary source of distortion and residual stresses is differential temperatures from the center of the part to the surface or from different locations on the surface. By reducing the thermal gradients and differential temperatures, large reductions in residual stresses and distortion can be achieved. The most significant factors that cause large thermal gradients in parts during quenching are temperature, agitation, the quenchant chosen and contamination of the quenchant.

Temperature. Increasing the oil temperature can reduce the distortion and residual stresses in a heat-treated component. As the oil temperature is increased, the temperature gradients in the part are decreased. This is the basic principle of martempering. Using increased temperature can also reduce thermal gradients in cold oils, up to the recommended use temperature of cold oil (typically 180–200ºF). Interestingly, the speed of cold oil can be increased by warming to approximately 160ºF.

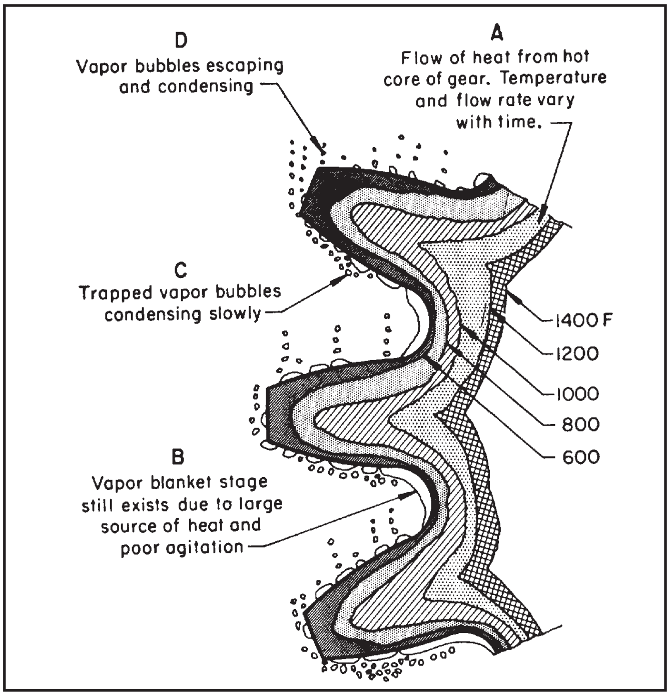

Figure 7—Creation of non-uniform quenching by inadequate agitation (after Ref. 3).

Agitation. Distortion occurs because of differential (Ref. 3.) temperature gradients, whether from the center to the surface or from surface to surface.

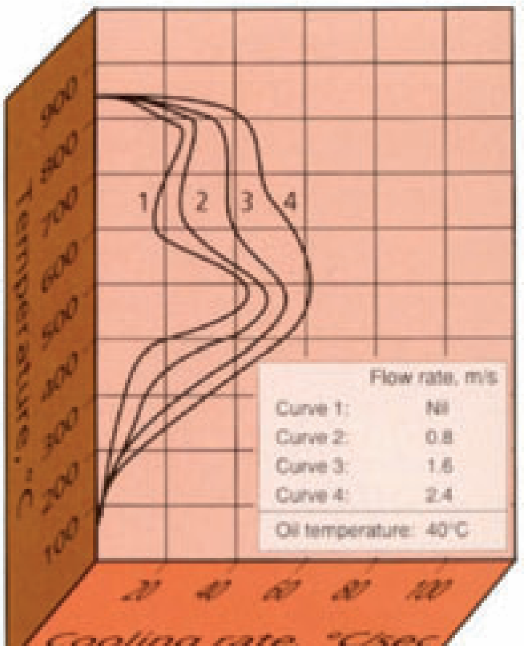

Figure 8—The effect of agitation on the quenching characteristics of a normal speed oil.

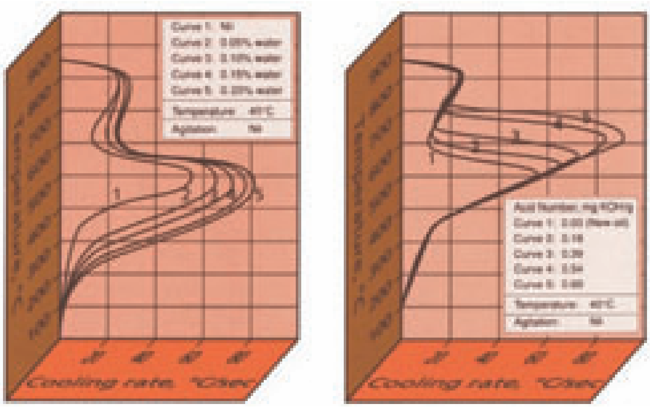

Figure 9—The effect of water and contamination on the characteristics of a normal speed quenching oil.

All three phases of cooling occur in the piece at different times. At times, all three phases can be present—which means that some areas are cooled very slowly, while other parts are cooled rapidly. This has the effect of creating thermal gradients on the surface of the part, which can cause distortion (see Fig. 7). The purpose of agitation is to minimize these surface gradients.

Quenching characteristics are influenced significantly by the degree of agitation for a normal speed quench oil under varying degrees of propeller agitation, as shown in Figure 8. It can be seen that increasing the degree of agitation reduces the stability of the vapor phase and increases the maximum rate of cooling. This also minimizes any vapor pockets and ensures that the part has uniform heat transfer across the surface.

However, too much agitation can have the same effect as too little agitation. If the agitation rate is too excessive, then the parts are cooled too rapidly. Large internal thermal gradients occur, and distortion results from the creation of large thermal gradients center-to-surface.

Quenchant. As was discussed previously, there are many types of petroleum-based quenchants. For most gear heat-treating applications, the use of marquenching oils is applied almost exclusively because of the benefits of reducing distortion. However, there are certain applications where cold oils are used, specifically in very large sections, or where press quenching occurs.

Contamination and Oxidation. The condition of the quench oil can also contribute to distortion of gears. Contamination of quenching oils with water must be avoided at all cost. As little as 0.05% of water in quenching oil influences quenching characteristics significantly and may cause soft spots, distortion or cracking (see Fig. 9). At concentrations of 0.5% or more, foaming during quenching is likely, and this can give rise to fires and explosions. Other contaminants, such as hydraulic oil and fire-resistant hydraulic fluids, can also alter the quenching characteristics, resulting in increased distortion and residual stresses.

The oxidation of a quenching oil, measured by the precipitation number or total acid number, is an indication of the level of oxidation of the quenching oil. As the oil oxidizes, it forms organic acids. As shown in Figure 9, the formation of oxidized constituents decreases the stability of the vapor phase and increases the maximum cooling rate. This can increase the risk of distortion and cracking. The use of stable, high quality quench oils will reduce the possibility of this occurring, as will the use of a proactive maintenance program of monthly or quarterly checks for contamination and oxidation.

Racking. Racking of gears is critical in minimizing the distortion. Parts must be located so that the applied agitation will ensure uniform heat transfer on all surfaces of the gear. Uniformity of heat transfer will minimize the formation of thermal gradients on the surface of the parts. The parts must be located so as not to create hot spots from adjacent parts or create mechanical damage from part-to-part interactions.

There are two primary methods for quenching parts. The first method is the use of a press quench. This is a specialized technique involving the physical restraint of distortion-prone parts on close-tolerance fixtures during the quenching operation. It minimizes distortion and movement and is used mainly during the quenching of bearing rings and automotive transmission ring gears. It is a highly manually-intensive operation, as each gear must be removed from the furnace manually and placed on a quench fixture. The press is actuated, and a large flow of quenchant is passed through the fixture. Highly accurate and low distortion parts can be achieved in this manner.

There are several disadvantages to this technique. As indicated above, it is manually intensive, although some robotic applications have been implemented. Because hydraulic fluids are used to actuate the dies, contamination of the quenchant is a problem. This can cause a change in the cooling rate and quenching characteristics, which can cause cracking or fires. If fire-resistant hydraulic fluids are used, then some spots or cracking can occur on the part or the close-tolerance fixture. The quenchant must be routinely checked for contamination and water content. The close-tolerance fixtures used in quench pressing are expensive to manufacture and must be designed for each gear configuration. Should the gear dimensions change, then a new fixture must be designed. Further, the life of the die is finite because of the thermal stresses experienced by the fixture. Distortion and cracking of the fixture can also cause its premature replacement. As a general rule, cold oils are used to harden the parts. This technique is generally limited to flat and symmetrical parts, such as ring gears.

The second method of quenching gears is to place them on a grid or fixture. Many gears can be heat treated in this fashion, greatly improving production rates. However, there are many ways to rack a gear that often depend on the type of furnace, quenchant, and the preference of the metallurgist.

Typically, ring gears are either laid flat on a grid or stacked several high. They can be offset, or stacked directly on top of each other. They are often hung, with supports under the gear.

Either has benefits that depend on the configuration of the gear. If gears are laid flat, they will tend to bend, or "potato-chip," with gears on the bottom and top of the load most prone to this type of distortion. This is due to differential cooling of the gears. In this case, the thermal mass of the grid retains heat, while the upper surface of the gear experiences the full quenching effect of the oil. The upper surface contracts due to thermal contraction, while the lower surface cools slower and does not experience as much thermal contraction. As the upper surface cools to a point where the martensitic transformation occurs, a volume change occurs, placing the upper surface in tension. When the lower surface cools, and its martensitic transformation occurs, a stress reversal places the upper surface in tension and the lower surface in compression. This is complicated by the round shape of the part, so that some areas bow up while other areas bow down, resulting in the "potato chip" shape. The degree of distortion is often dependent on how stiff the section is (polar moment of inertia). This can be overcome by the proper design of racking fixtures.

One thing that is important, when gears are laid flat on a grid, is that the grid itself is flat. Because the material being heat treated is hot and soft, it will conform to the shape of the grid. If the grid is in poor condition and badly warped, then parts laid on it will tend to be warped in a similar fashion. It is very important that proper care be taken with supporting grids, and to discard those grids that are warped or badly cracked. Grids and racks should be routinely stress-relieved to relieve the buildup of quenching stresses over time. This will also extend the life of expensive grids and help minimize cracking.

When parts are hung, the weight of the gear often causes the gear to distort, with the gear becoming the shape of an oval. The degree of ovality often depends on the quality of support and the weight of the part. Smaller parts, fully supported, will tend to distort less. Properly designed supports minimize distortion and provide for uniform heat transfer. One advantage of hanging gears, is that all sides will experience similar heat transfer, assuming no hot spots or proximity of other parts (creating hot oil spots).

Spiral bevel pinion gears are racked vertically. It is preferred that the heavy section is down and is the first to quench. Often, the pinions are offset to allow uniform heat transfer and the minimization of hot spots. Spacers are usually used to maintain the pinions vertically and to prevent movement of the parts.

Modeling of Quenching

Computational fluid dynamics (CFD). Computational Fluid Dynamics (CFD) is a computer model of the flow of fluid. It has been used extensively in the aerospace field to simulate the flow around airframes and structures. This enables the creation of a virtual model to avoid expensive wind tunnel testing and the design and creation of very expensive instrumented wind tunnel models.

CFD is very computationally intense. Previously, it required the use of specialized CRAY supercomputers or networked RISC workstations. However, because of the increase in computing capability and improved algorithms, fairly complex CFD models can now be performed on everyday office computers or laptops. There are three major steps in creating a CFD simulation: preprocessing, solving the mesh, and post-processing.

Preprocessing. Preprocessing is the first step in building and analyzing a flow model. It includes building the model (or importing from a CAD package), applying a mesh, and entering the data. A mesh is created using geometrical shapes, such as cubes, "bricks," or tetrahedral shapes. Data is entered about the fluid, such as viscosity, temperature, inlet velocities, fluid density, etc.

Solving the mesh. After preprocessing, the CFD solver does the calculations and produces the results. The flow characteristics of the mesh are determined by solving the Navier-Stokes equations at each node or corner of the mesh. This is a very computationally intensive step and can consume many thousands of CPU cycles, depending on the complexity of the mesh.

Post-processing. Post-processing is the final step in CFD analysis and involves organization and interpretation of the data and images. An example of the results of a CFD analysis is shown in Figure 10.

The use of CFD allows designing "virtual" quench tanks to examine fluid flow within them and to simulate the interaction

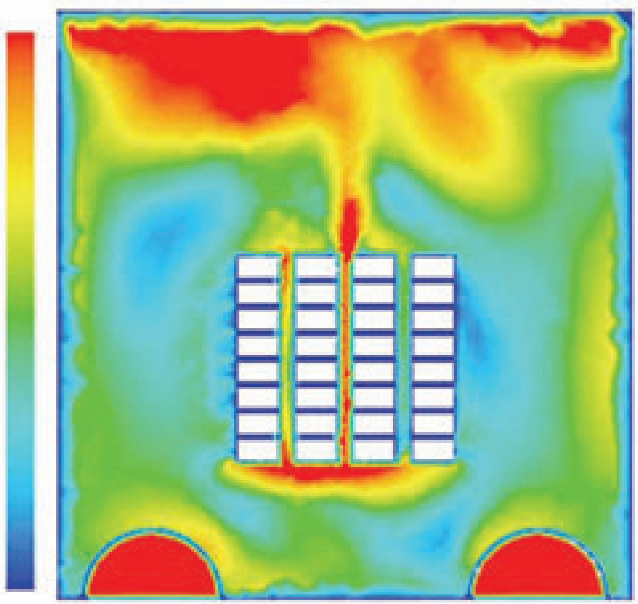

Figure 10—Results of a CFD analysis of a quench tank, showing variations in agitation.

of fluid flow with the parts. CFD is commonly used to design quenching systems and to evaluate the effect of changes to the quench tank. It can be used as an aid to understand distortion problems. It can also be used to examine the effect of different racking methods. Capable of looking at the "whole-picture," CFD examines hot spots that occur because of part interactions. Because of this ability to examine the entire quench agitation system, it is extremely useful for modeling racking and thermal gradients in the quenchant.

Because of the availability of cost-effective software and improved user interfaces, CFD is a tool that will have increasing applications in solving heat-treating and quenching problems.

Finite element analysis (FEA) of part distortion. Determining the distortion of a part during heat-treating or predicting the microstructure of a part has been a long-held goal of the heat-treating industry. However, this goal has been elusive. Finite element analysis (FEA) has been used extensively to solve structural and performance issues of components. It has only recently been used in predicting part distortion or part microstructure.

To accurately predict distortion or the formation of residual stresses in a part requires an understanding of many factors. These factors include heat transfer, elastic-plastic stress and strain behavior, and microstructure.

Heat transfer is not a steady-state condition. It requires the determination of heat-transfer coefficients as a function of fluid properties, geometry, surface condition, and agitation. It is also time- and location-dependent.

Analyzing elastic-plastic stress and strain behavior requires detailed constitutive models of stress and strain as a function of strain rate, location and temperature.

Knowledge of the diffusion transformations (pearlite and bainite) occurring in the component, as well as the non-diffusion transformations (austenite to martensite transformation, recrystallization, grain growth, etc.) is necessary to accurately predict the microstructure development and its contribution to distortion and residual stresses.

All of these factors (heat transfer, microstructure and elastic-plastic strain) are necessary to effectively model the residual stresses and distortion occurring in a component.

Advantages of FEA modeling of part distortion are many. **These include**:

- Enabling the distortion and residual stresses in a heattreated part to be quantified;
- Examining the effect of part geometry and racking on the development of distortion and residual stresses, includ ing alternative part geometries and racking techniques prior to part creation or heat treatment; and
- Examining causes of failure due to quench cracking or high residual stresses.

Disadvantages of this technique include:

- The technique is computationally intensive. Because of the complexities described above, the learning curve is steep. A skilled engineer is necessary for accurate results.
- Detailed heat transfer, elastic-plastic and microstructure constitutive models must be known. This may require extenive laboratory and field testing for the initial model and verification.
- There is difficulty in measuring and verifying residual stresses. In addition, previous processes play a critical role in the development of distortion and residual stresses. These previous processes are often beyond the scope of cur rent modeling capability.
- There is the limitation of modeling a single part. Since the heat transfer conditions change from part to part depending on racking and agitation, it is very difficult to understand and model an entire quench load.
- The use of finite element modeling of microstructure development and the development of residual stresses and distortion is in its infancy. With the creation and applica tion of better constitutive models, this technique offers great potential in solving many distortion problems before the part enters the furnace.

Conclusion

An effort was made to explain the three phases of quenching and the effect that the quench path has on the development of distortion and residual stresses. The formation of residual stresses from non-heat-treating sources was examined and discussed. The variables affecting the distortion of gears during heat treatment and quenching were illustrated. Finally, methods of characterizing the distortion and residual stresses using computer modeling were described. The limitations of different types of modeling (CFD and FEA) were examined.

References
1.Kunitake, T. and S. Susigawa, Sumitomo Search, May 1971, p. 16–25.
2.Thelning, K.E. *Steel and Its Heat Treatment,* Butterworths Publishing, London, 1985, p. 584.
3.MEI Course 6, *Heat Processing Technology*, "Quenching Media and Equipment," ASM, 1977, p.2.

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