WHITE PAPER

INSIGHT INTO HEAT TREATMENT AND QUENCHING OF GEARS

By D. Scott MacKenzie, PhD, Technical Specialist

Abstract

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 after heat treatment are often distorted or stained. It is often the "black-hole" that 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 corrective 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 product quickly and cost-effectively (Figure 1). 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.

Figure 1 - Typical furnace used for the heat treatment of gears.

In metallurgy the definition of quenching is "the controlled extraction of heat" [1]. 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 the liquid quenchant, there are normally 3 stages of quenching [2]. The 3 stages of quenching are:

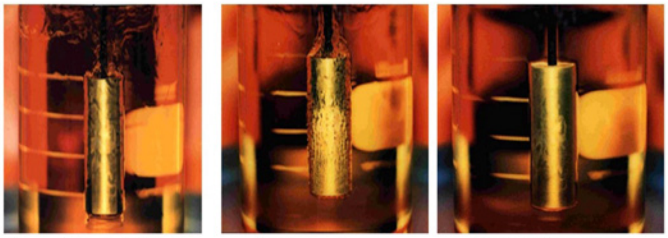

Figure 2 - Three stages of quenching evident on a cylindrical probe quenched in oil from 1600°F.

- 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 hot 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 they are allowed to persist undesirable micro-constituents can form.

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.

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The high heat extraction rates are due to carrying away heat 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 added to enhance the maximum cooling rates obtained by a given fluid. The boiling stage stops when the temperature of the component's surface reaches a temperature 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 see 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 boiling temperature. Heat is removed by convection and 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 slowest of the 3 stages. Typically, it is this stage where most distortion occurs. An example showing the three stages of quenching is shown in Figure 2.

Obtaining properties and low distortion is usually a balancing act [3]. Often, optimal properties are obtained at the expense of high residual stresses or high distortion. Low distortion or 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.

To achieve proper strength and toughness, it is necessary to convert Austenite to Martensite, which is then tempered to form the proper tempered Martensite 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 (Figure 4). The rate of the critical quench rate is dependant 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 cooling rate and be fully hardened, but the center cools more slowly and forms a soft Pearlitic or Bainitic microstructure (Figure 5).

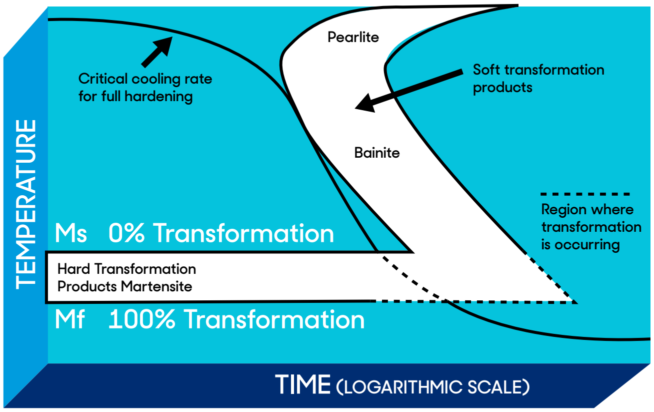

Figure 4 - A Time-Temperature-Transformation diagram illustrating the critical cooling rate for complete martensitic transformation.

Hardenability is the ability of steel to through-harden [4]. It is not the ability of the steel to get hard. In a sense, it is a measure of the critical cooling rate on the TTT curve.

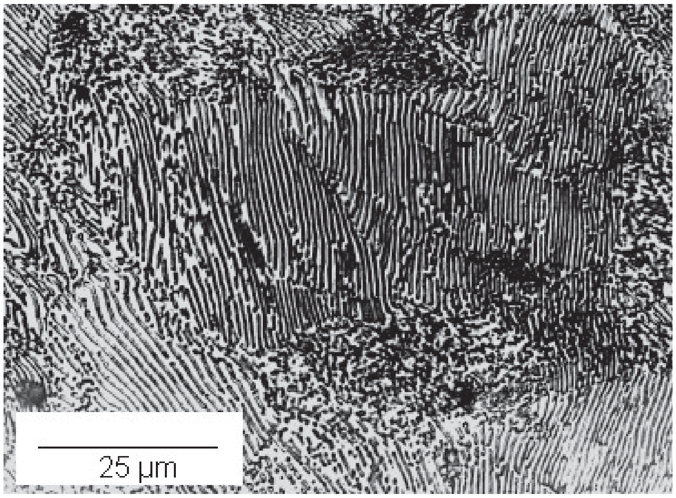

Figure 5 - Pealite resulting from slowly quenched high-carbon steel.

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Increasing the hardenability of steel is accomplished by increasing the alloying content of the steel. Manganese, Chromium and Molybdenum are all effective alloying elements that increase the hardenability of the steel. These alloying elements cause a delay in transformation, by shifting the transformation curve to the right. This reduces the critical cooling rate for Martensitic transformation (Figure 6). Alloying elements may not always be beneficial to other processes such as machining or forging.

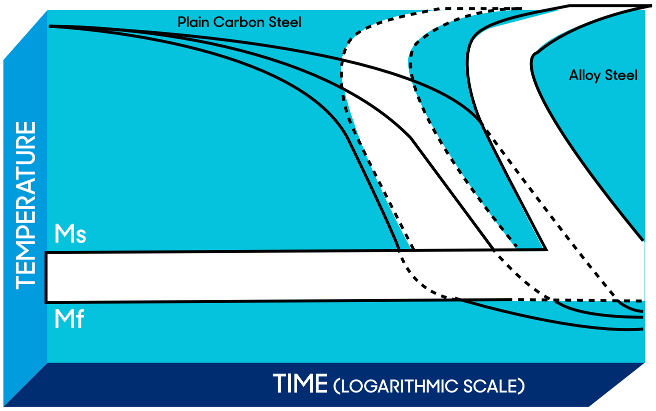

Figure 6 - The effect of alloy content on steel hardenability.

Increasing the alloying content is not a simple panacea. Increasing the carbon content, and alloying content can also have deleterious effects, by lowering the Martensite-Start Transformation Temperature (Ms). Increasing the carbon content, while shifting the TTT curve to the right, significantly lowers the Ms temperature (Table 1). Alloying elements also increase the "effective carbon" content according to the formula [5]:

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

Cracking and distortion increases as the "effective carbon" content increases. Alloys become prone to distortion and cracking as the "effective carbon" exceeds 0.52% [6]. This tendency is decreased by the proper application of quenchants. A fast enough quenchant is used that will achieve the desired properties, but slow enough that cracking or excessive distortion will not occur.

Table 1 - Martensite Start Transformation Temperature (Ms) as a function of carbon content.

CARBON CONTENT	MS TEMPERATURE
0.2%	430°C
0.4%	360°C
1.0%	250°C

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 International Standards Organization (ISO 9950) [7].

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 7 for both normal speed and high speed quenching oils.

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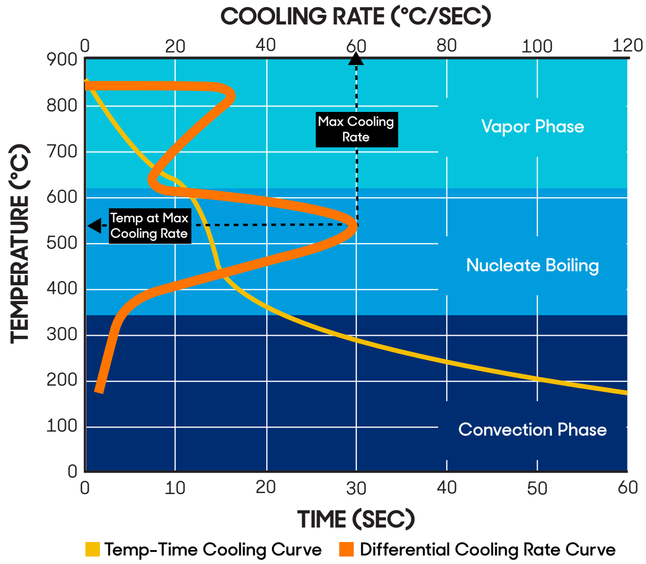

Figure 7 - Temperature-time cooling curve and the differential cooling rate curve.

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 and it can, therefore, 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.

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, and particular sperm whale oil have been used for quenching operations. The first petroleum-based quenching oils were developed around 1880 by E.F. Houghton in Philadelphia. Since that time, much advancement have 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. The addition of complex anti-oxidant 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 [8].

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. Quench oils can be classified as normal, medium or high speed quench oils.

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 8.

Mar-quenching oils are a special case where the part is quenched into a quenchant at elevated temperature, typically 100-200°C. The work piece is held in the quenchant until temperature equilibrium is established throughout the section, and then air-cooled to ambient temperature.

During mar-quenching, components are quenched to an intermediate temperature close to the Ms temperature, and held at this temperature. This eliminates the temperature gradients across the surface, and consequently, during subsequent slow cooling after removal from the hot oil, transformation to Martensite occurs uniformly throughout the section (Figure 9).

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This minimizes the generation of internal stresses and reduces distortion.

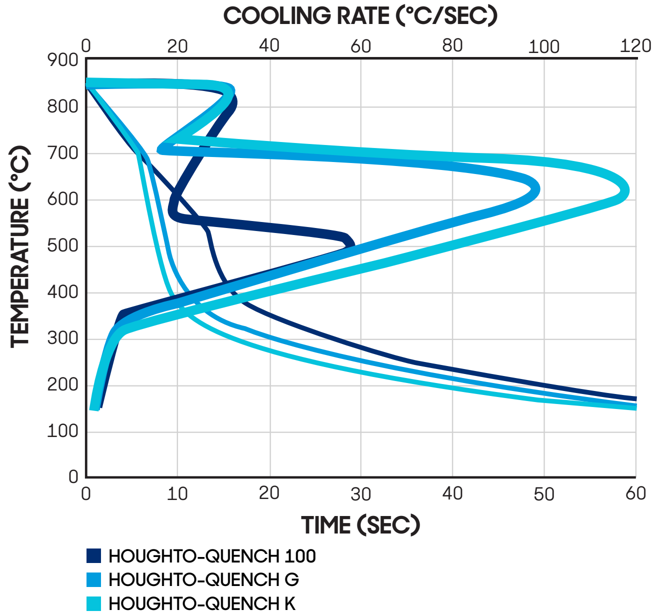

Figure 8 - Comparison of fast, normal and slow quench oils.

Since mar-quenching 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 anti-oxidant packages to provide long life. Selection of the mar-quenching oil is based on the operating temperature and quenching characteristics. A minimum of 50°C should be maintained between the operating temperature of the oil and its flash point.

However, the source of distortion and residual stresses are not limited to either 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 are illustrated in Figure 10 [9].

Isothermal Transformation Diagram

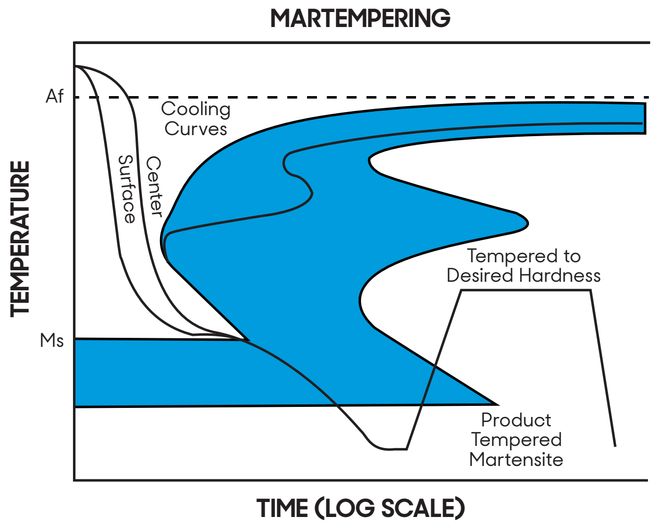

Figure 9 - Schematic of mar-quenching to minimize distortion [1].

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 (Figure 10) 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.

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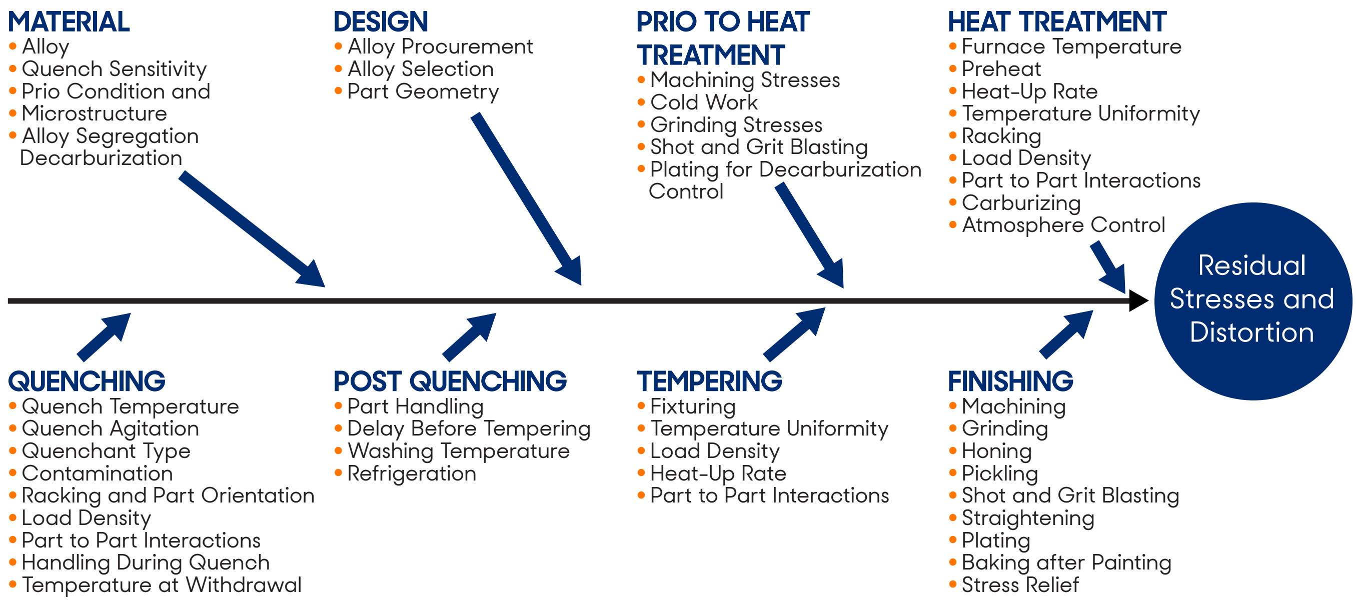

Figure 10 - Fishbone diagram of the potential causes of residual stresses and distortion.

Material - The alloy chosen can play an important role in how sensitive a part is to distortion during quenching. If the equivalent carbon Ceq is greater than 0.52, it is prone to high residual stresses from transformation stresses, and is prone to cracking. 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 which 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, and distortion or cracking can result. 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 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 that these operations must operate to be profitable, a large amount of residual stresses can be created in the part, which 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.

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

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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 [9]. Proper racking minimizes part-to-part interactions, as well as allows heat to reach all parts. It further allows the quenchant to evenly extract the heat from parts in a uniform fashion.

One area that is often overlooked in the control of distortion and residual stresses, is the role that atmosphere plays. Most gears are carburized to achieve a hardwearing 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 [4]:

$$\frac{\Delta V}{V} x100 = 1.68(100 - V_C - V_a) + V_a(2.21C - 4.64)$$

where △V is the change in volume; Vc and Va are the volume fractions of carbon and austenite; and C is the concentration of carbon in the steel. 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 a distorted part to occur immediately after heat treat, these strains can appear immediately after any subsequent machining steps, as the part tries to achieve a new static equilibrium.

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 10, 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 largest factors that effect the creation of 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 temperature of oil is increased, the temperature gradients in the part are decreased. This is the basic principle of mar-tempering. Using increased temperature can also reduce thermal gradients in cold oils, up to the recommended use temperature of cold oil (typically 180-200°F). Interestingly, the speed of cold oil can be increased by increasing the temperature of the oil to approximately 160°F.

Agitation - Distortion occurs because of differential temperature gradients, whether from the center to the surface; or from surface to surface. As can be seen in Figure 3, all three phases of cooling 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 (Figure 11). The purpose of agitation is to minimize these surface gradients.

Quenching characteristics are influenced significantly by the degree of agitation, as shown in Figure 12 for a normal speed quench oil under varying degrees of propeller agitation. 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 has the benefit of minimizing any vapor pockets that can occur, and ensuring that the part has a uniform heat transfer across the surface of a part.

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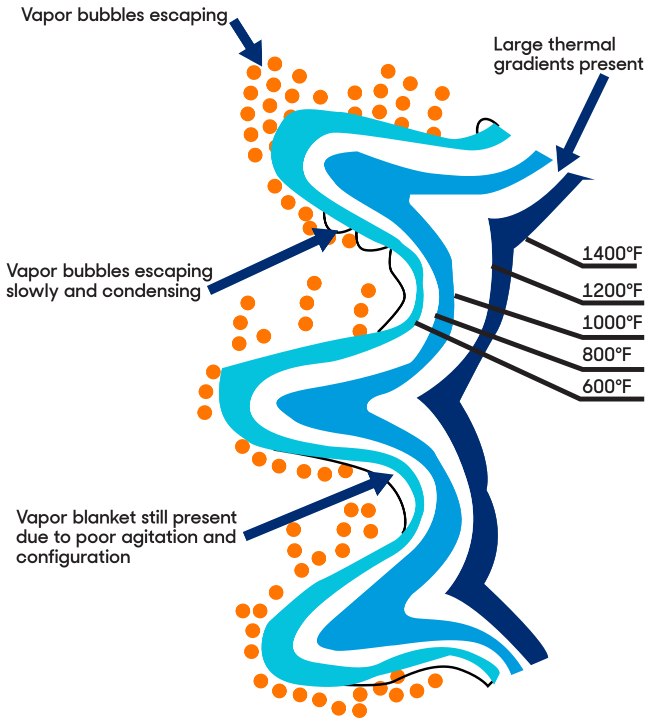

Figure 11 - Creation of non-uniform quenching by inadequate agitation.

Quenchant - As was discussed previously, there are many types of petroleum-based quenchants. For most gear heat-treating applications, the use of mar-quenching oils is used 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 is used.

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 (Figure 13).

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.

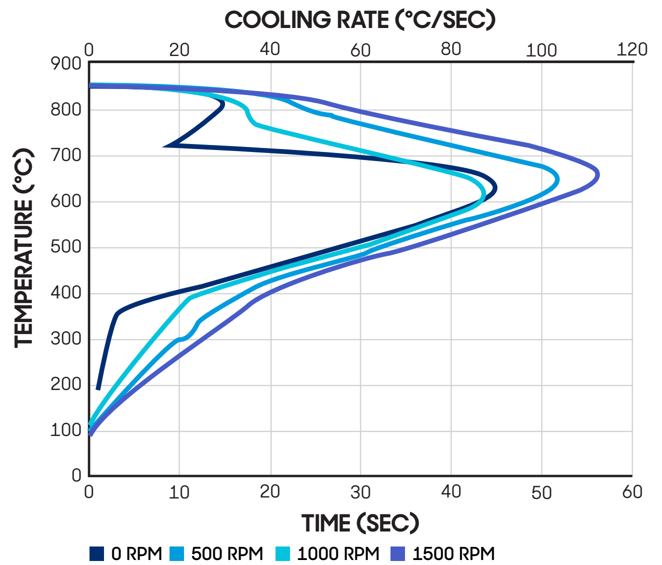

Figure 12 - The effect of agitation on the quenching characteristics of a normal speed oil.

There are several disadvantages to this technique. As was indicated above, it is manually intensive, although some robotized 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 of the quenchant, 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

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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 dies in finite because of the thermal stresses experienced by the fixture. Distortion and cracking of the fixture can also cause premature replacement of the fixture. 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.

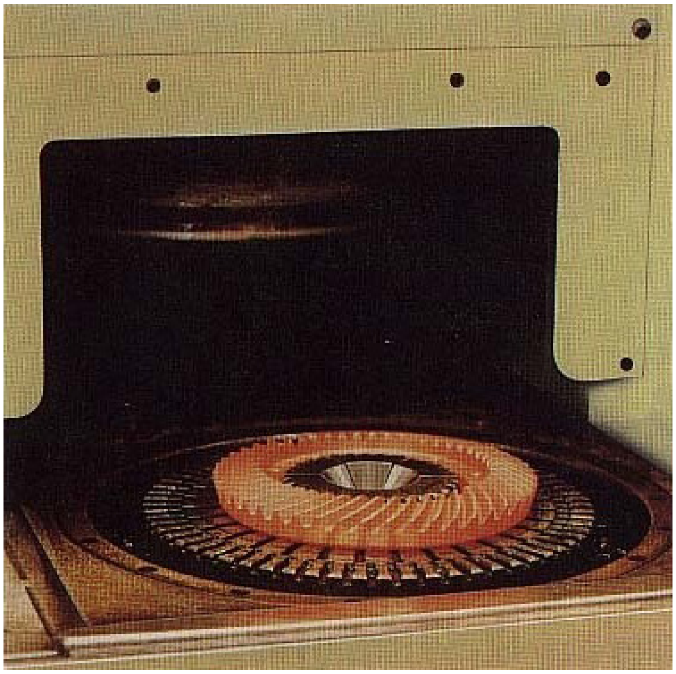

Figure 13 - Press quenching of an automotive ring gear.

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 depends on the type of furnace, quenchant, and the preference of the metallurgist.

Typically, ring rears are either laid flat on a grid and stacked several high (Figure 14). They can be offset, or stacked directly on top of each other. They are often hung, with supports under the gear. Either method has benefits that depend on the configuration of the gear.

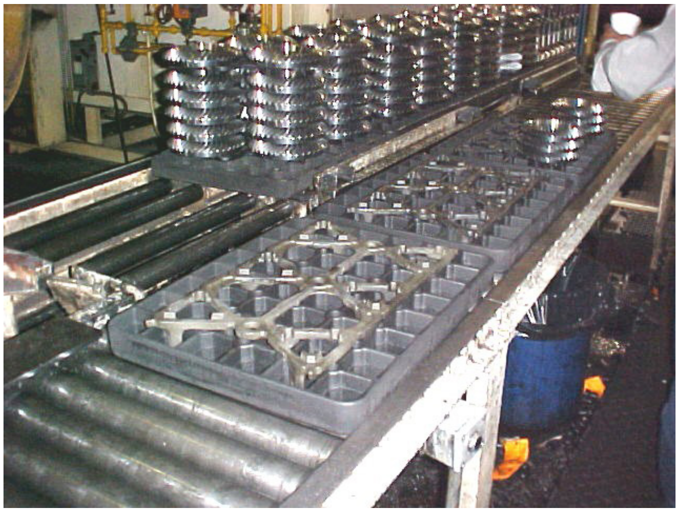

Figure 14 - Typical racking of gears on a grid prior to quenching.

If gears are laid flat, they will tend to bend, or "pota-to-chip", with gears on the bottom of the load and the 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 appoint where the martensitic transformation occurs, a volume change occurs, placing the upper surface in tension. When the lower surface cools, and the martensitic transformation occurs, a stress reversal occurs, placing 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 dependant on how stiff the section is (polar moment of inertia). This can be overcome by the proper design of racking fix-tures. Figure 15 shows examples of properly racked parts to minimize distortion during quenching, and to allow the parts to be evenly heated.

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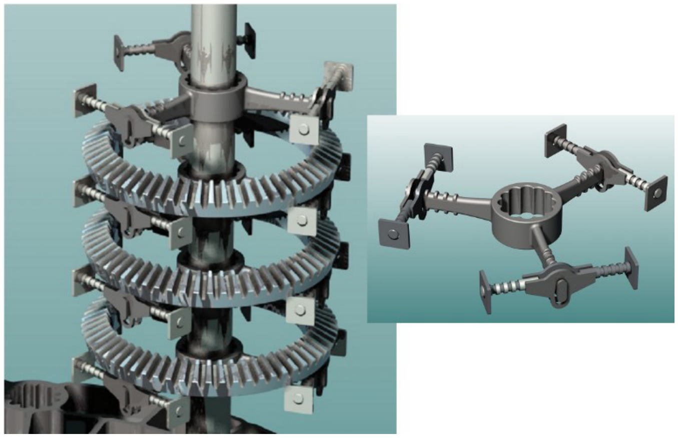

Figure 15 - Example illustrating proper racking design to minimize distortion.

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 oils spots).

Figure 16 - Racking of pinions to minimize distortion.

Pinion gears are racked vertically (Figure 16). 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 vertical, and to prevent movement of the parts.

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 (Figure 17). At concentrations of 0.5% or more, foaming during quenching is likely and this can give rise to fires and explosions. Other contaminates, such as hydraulic oil, and fire resistant hydraulic fluids can also alter the quenching characteristics, resulting in increased distortion and residual stresses.

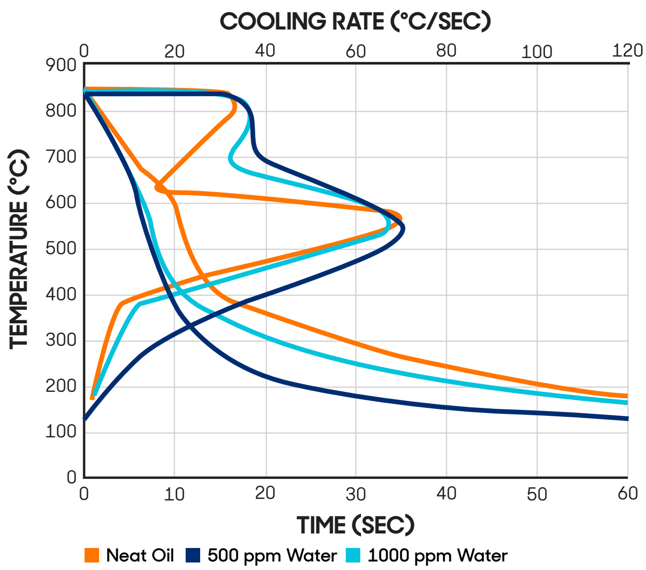

Figure 17 - The effect of water on the characteristics of a normal speed quenching oil.

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 17, 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.

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The life of quench oil is also dependant on the level of oxidation. If the oxidation of the oil is high, then the oil is prone to staining, resulting in shortened quench oil life. The use of a proactive maintenance program of monthly or quarterly checks for contamination and oxidation is necessary to reduce staining and prolong oil life.

Modeling of Quenching

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 enable a virtual model to be created 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 super computers 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.

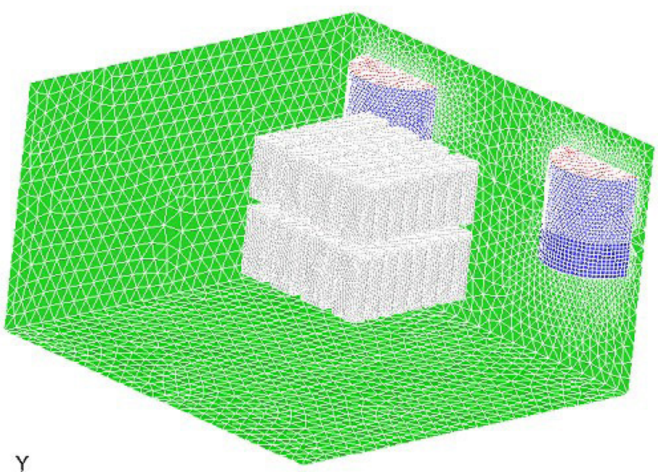

Figure 18 – Example of a meshed grid in a hypothetical quench tank.

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 computational 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 19.

The use of CFD allows designing "virtual" quench tanks, to examine fluid flow within a quench tank, and to simulate the interaction 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 [10] [11] [12] [13].

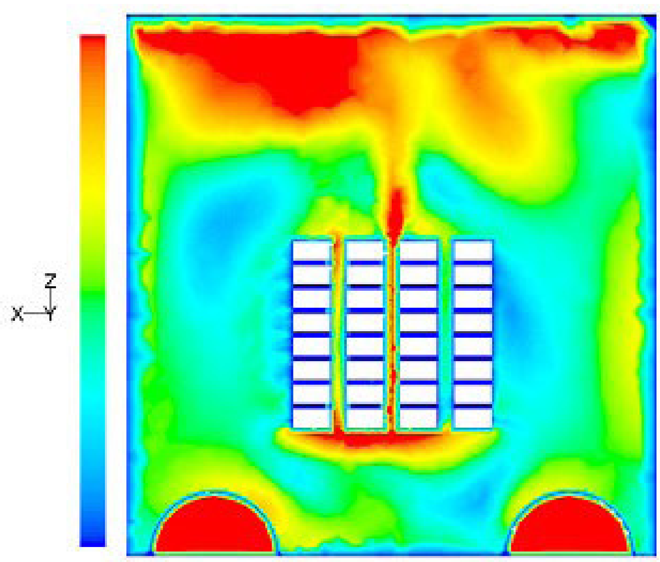

Figure 19 – Results of a CFD analysis of a quench tank, showing variations in agitation.

It can be used as an aid to understand distortion problems, by analyzing fluid flow around the part. It can also be used to examine the effects of different racking methods. It is also capable of looking at the "whole-picture", and examine hot spots that occur because of part interactions.

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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 application 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. The use of Finite-element-analysis (FEA) has been used extensively to solve structural and performance issues of components for a long time. 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 and understanding of many factors. These factors include heat transfer, elastic-plastic stress and strain behavior and microstructure.

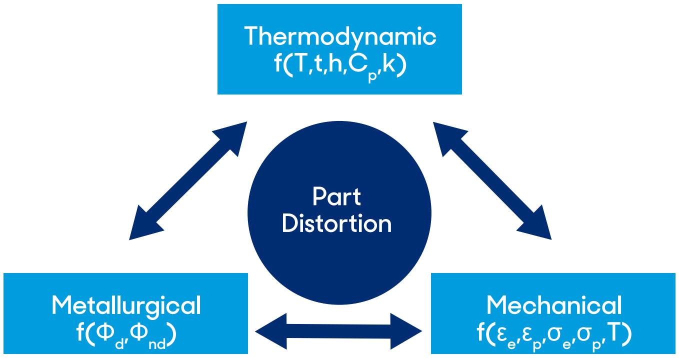

Figure 20 - Interaction of variables occurring during modeling of part distortion.

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

Elastic-plastic stress 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 strains) are necessary to effectively model the residual stresses and distortion occurring in a component. The interrelationship of these factors is shown in Figure 20 with a simple model in Figure 21.

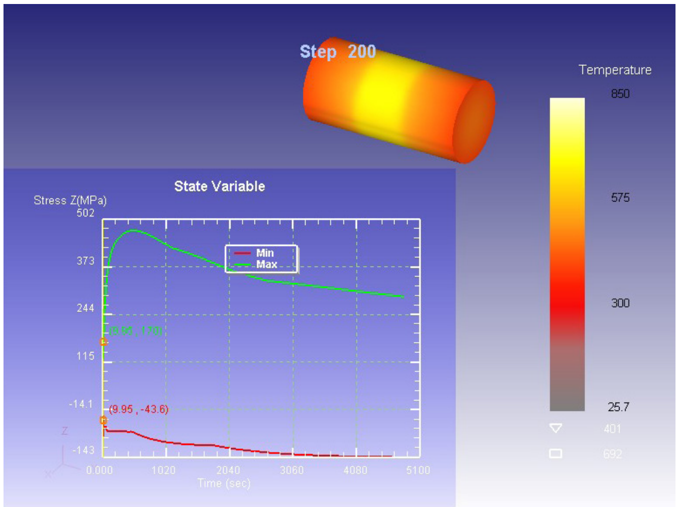

Figure 21 - Simple geometry modeled, showing the development of residual stresses.

Advantages of FEA modeling include:

- Quantifying the distortion and residual stresses in a heat-treated part.
- Examining the effect of part geometry and racking on the development of distortion and residual stresses.
- Alternative part geometries and racking techniques can be examined prior to part creation or heat treatment.
- 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.
- Detailed heat transfer, elastic-plastic and microstructure constitutive models must be known, requiring extensive laboratory and field-testing.

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- Difficult to measure and verify residual stresses. However, previous processes play a critical role in the development of distortion and residual stresses, perhaps causing erroneous results
- 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 and 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 availability of better constitutive models, this technique offers a 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 were 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.

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