case-hardening steels, increases warpage on quenching (Ref 80)

- Tight (that is, thin and highly adherent) scale and decarburization, at least in certain areas. Tight scale is usually a problem encountered in forgings hardened from direct-fired gas furnaces having high-pressure burners. Quenching in areas with tight scale is extremely retarded compared to the areas where the scale comes off. This produces soft spots, and, in some cases, severe unpredicted distortion. Some heat treaters coat the components with a scale-loosening chemical prior to their entry into the furnace (Ref 79). Similarly, the areas beneath the decarburized surface do not harden as completely as the areas below the nondecarburized surface. The decarburized layer also varies in depth and produces an inconsistent softer region as compared to the region with full carbon. All these factors can cause a condition of unbalanced stresses with resultant distortion (Ref 79)
- Long parts with small cross sections ($L = 5d$ for water quenching, $L = 8d$ for oil quenching, and $L = 10d$ for austempering, where $L$ is the length of the part, and $d$ is its diameter or thickness)
- Thin parts with larger areas ($A = 50t$, where $A$ is the area of the part, and $t$ is its thickness)
- Unevenness of, or greater variation in, section

**Examples of Distortion**

**Ring Die.** Quenching of ring die through the bore produces the reduction in bore diameter as a result of formation of martensite, associated with the increased volume. In other words, metal in the bore is upset by shrinkage of the surrounding metal and is short when it cools (Ref 24). However, all-over quenching causes the outside diameter to increase and the bore diameter to increase or decrease, depending upon precise dimensions of the part. When the outside diameter of the steel part is induction- or flame-hardened (with water quench), it causes the part to shrink in outer diameter (Ref 63). These are the examples of the effect of mode of quenching on distortion (Ref 81).

**Thin Die.** (with respect to wall thickness) is likely to increase in bore diameter, decrease in outside diameter, and decrease in thickness when the faces are hardened. If the die has a very small hole, insufficient quenching of the bore may enlarge the bore diameter because the body of die moves with the outside hardened portion.

**Bore of Finished Gear.** Similarly, the bore of a finished gear might turn oval or change to such an extent that the shaft cannot be fitted by the allowances that have been provided. Even a simple shape such as a diaphragm or orifice plate may, after heat treatment, lose its flatness in such a way that it may become unusable.

**Production of Long Pins.** In the case of the production of long pins (250 mm long × 6 mm diameter, or $10 \times \frac{1}{4}$ in.) made from medium-alloy steel, it was found, after conventional hardening, that when mounted between centers, the maximum swing was over 5 mm (0.20 in.). However, the camber could be reduced to within acceptable limits by martempering, intense or press quenching.

**Hardening and Annealing of Long Bar.** When a 1% carbon steel bar, 300 mm long (or more) × 25 mm diameter (12 in. long, or more, × 1 in. diameter), is water quenched vertically from 780 °C (1435 °F), the bar increases both in diameter and volume but decreases in length. When such bars are annealed or austenitized, they will sag badly between the widely spaced supports. Hence, they should be supported along their entire length in order to avoid distortion.

**Hardening of Half-Round Files.** Files are usually made from hypereutectoid steel containing 0.5% chromium. Files are heated to 760 °C (1400 °F) in an electric furnace after being surface coated with powdered wheat, charcoal, and ferrocyanide to prevent decarburization. They are then quenched vertically in a water tank. On their removal from the tank, the files appear like the proverbial dog’s tail. The flat side has curved down, the camber becomes excessive, and the files can no longer be used in service. One practical solution is to give the files a reverse camber prior to quenching. The dead flat files could, however, be made possible, and the judgment with regard to the actual camber needed depends upon the length and the slenderness of the recut files (Ref 82).

Similarly, when a long slender shear knife is heat treated, it tends to curve like a dog's tail, unless special precautions are taken.

**Hardening of Chisels** (Ref 63). Chisels about 460 mm (18 in.) long and made from 13 mm (0.5 in.) AISI 6150 bar steel are austenitized at 900 °C (1650 °F) for 1.5 h and quenched in oil at 180 °C (360 °F) by standing in the vertical position with chisel point down in special baskets that allow stacking of two 13 mm (0.5 in.) round chisels per 650 mm²
The portion of the bar that touches the basket cools slowly, producing uneven contraction and thermal stress. The martensite formation is delayed on the inner or abutting side of the bar, causing unequal expansion during transformation. This distortion can be eliminated or minimized by loading the parts in the screen-basket in such a way that stacking arrangement permits sufficient space between each part and by slightly decreasing the austenitizing temperature (Ref 62). Distortion can also be minimized by austempering the part, provided that the carbon content is on the high side of specification to produce the lower bainitic structure of 55 to 57 HRC. If higher yield stress is not warranted, only chisel ends need hardening and subsequent tempering (Ref 63).

**Hardening of a Two-Pounder Shot.** The hardness of a two-pounder shot was specified at 60 HRC on the nose and 35 HRC at the base. A differential hardening technique was performed on the shot made of a Ni-Cr-Mo steel. This technique consisted of quenching the shot in the ice-cold water by its immersion in a tank up to the shoulder, followed by drawing out the water from the tank at a stipulated rate until the water line reached the base of the nose. The final step involved withdrawing the shot from the tank when completely cold. The back end was then softened by heating in a lead bath after initial tempering. The first few shots hardened in this way were observed to split vertically across the nose. The failure was, however, avoided by withdrawal of the shot before attaining ice-cold temperature and its subsequent immersion in warm water (Ref 82).

**Hardening of a Burnishing Wheel.** In the manufacture of railway axles, the gearing surface on which the axle rests in the housing has to be given a high burnishing polish employing a circular pressure tool that is made of 1.2C-1.5Cr steel. For satisfactory results, the hardness of the tool surface should be about 60 HRC. It has been found that the tool usually cracks before its withdrawal from the cold-water quenching bath. This problem may, however, be avoided by quenching the tool in water for 10 s prior to transferring it to an oil bath for finish quenching. Time quenching can be judiciously applied for many heat treatment problems of distortion or cracking. Stress-relieving treatment after the use of the tool for some time may also enhance its performance life. As indicated above, martempering is also one of the solutions for this problem (Ref 81).

**Hardening of Case-Carburized Mild Steel.** If oil-hardening steels are not available for making a component, mild steel parts are carburized and water quenched to obtain the desired hardness, possibly resulting in excessive distortion, which is very difficult to straighten without cracking.

**Hardening of Carburized Low-Carbon Steel Rollers.** The best course of quenching carburized En32 steel rollers (25 mm diam × ≥ 600 mm long, or 1 in. diam × ≥ 2 ft long), employed in textile printing, is to roll them down skids into water-quenching tanks because this produces less warpage than when quenched slowly with the bar either in vertical, horizontal, or inclined positions. These are the procedures adopted for hardening of cylinders with length considerably greater than the diameter.

**Hardening of Helix Gears.** The distortion of the helical gears made of IS 20MnCr1 grade steel (similar to AISI 5120) used as the third speed gear in the gear box of Tata trucks is an unavoidable natural consequence of the hardening process after carburizing. This type of distortion is linked with increased length and decreased diameter and occasionally increased helical angle (Ref 83). If the extent of distortion can be controlled, a constant correction to the helix angle can be imparted in the soft-stage manufacturing (machining) prior to heat treatment so that this correction can compensate for the distorted angle and may result in a gear with desired helix angle. Thus a constant magnitude of distortion without minimization is assured in every job of every batch of production in commercial manufacturing. However, the residual stress system and metallurgical properties such as core strength, case depth, surface hardness, proper microhardness in the surface regions, and so forth, are assured (Ref 84). Similarly, when heavy-duty tooth gear is gas carburized and quenched to harden the surface layer, the diameter and tooth span increase and tapering and bending also occur.

**Nitriding of Screw.** A rolling mill screw, after liquid nitriding, may also show a small decrease in length, which causes pitch errors in the screws (Ref 83).
Induction and Flame Hardening of Spur Gears. Spur gears, after induction and flame hardening, exhibit increased circular pitch, the error being maximum for the tooth groove quenched first. Similarly, in line-heating process, the thin plate undergoes convex bending and the thick plate concave bending (Ref 83).

Precautions

Inadequate support during the heat-treatment cycle, poorly designed jigs and quenching fixtures, or incorrect loading of the parts may cause distortion (Ref 73). In general, plain-carbon and low-alloy steels have such a low yield strength at the hardening temperature that the parts are capable of distorting under their own weight. Every care, therefore, must be taken to ensure that parts are carefully supported or suspended during heating; long parts are preferably heated in a vertical furnace or with the length in the vertical plane (Ref 85). They should be quenched in the vertical position with vertical agitation of the quenchants. Also, it must be remembered that many tool steels are spoiled by failure to provide enough support when they are taken out from the furnace for quenching. Thus, every precaution is taken to ensure that parts are adequately supported during entire heat treatment by employing well-designed jigs, fixtures, and so on.

Other precautions to minimize distortion include:

- Tool steels should be heated to hardening temperature slowly, or in steps, and uniformly. Hot salt baths are used to render fast, uniform heat input
- It is best to heat small sections to the lower region of the recommended hardening temperature range and to heat large sections at the higher temperature range. Overheating by employing too high a temperature or too long a heating time must be avoided
- It is a good practice to protect the surface of the component from decarburization (by packing it in cast iron chips or using a vacuum furnace, for example). If a separate preheating furnace is not available, the part can be put in a cold furnace, after which the temperature is raised to proper preheating temperature and kept at that temperature to attain uniform heating throughout, prior to proceeding to the hardening temperature (Ref 86)
- With the slower cooling rate, which is consistent with good hardening practice, a lower thermal gradient will be developed, thereby producing less distortion
- Thus rapid heating and cooling rates of irregularly shaped parts must be avoided
- Proper selection of quenchant with desirable quenching properties and adequate agitation during hardening must be provided

Methods of Preventing Distortion (Ref 82, 87)

Straightening is one method to remove or minimize distortion. Since straightening (after hardening) can largely relieve the desirable residual compressive stresses (in plain-carbon and low-alloy steels) that may cause breakage, it would be better to accomplish this before the steel cools below the Ms temperature, that is, when the steel is in the metastable austenitic state (Ref 35). This temperature is above 260 °C (500 °F) for most tool steels and is preferably about 400 °C (750 °F) for long shear knives, which are usually made of 2C-12Cr steel. Warping on parts such as shafts and spindles can be corrected by straightening during or after hardening, followed by grinding to size (Ref 84). Mostly high-alloy steels are straightened after hardening due to the higher percentage of retained austenite and their comparatively low yield stress. Straightening also can be accomplished during the tempering process (Ref 35). However, straightening of hardened parts with higher strength will cause a loss of fatigue properties and possibly initiation of cracks at the surface. Hence, straightening after the hardening treatment must be very carefully controlled and should be followed by a low-temperature tempering treatment.

The case-hardened (for example, nitrided, carburized) parts can be straightened to a very large extent as a result of their lower core hardness. Nitrided parts may be straightened at 400 °C (750 °F) (Ref 35).

Support and Restraint Fixtures. Fixtures for holding finished parts or assemblies during heat treatment may be either support or restraint type. For alloys that are subjected to very rapid cooling from the solution-treatment temperature, it is common practice to use minimum fixturing during solution treatment and to control dimensional relations by using restraining fixture during aging. Support fixtures are used when restraint type is not needed or when the part itself renders adequate self restraint. Long narrow parts are very easily fixtured by hanging vertically. Asymmetrical parts may be supported by placing on a tray of sand or a ceramic casting formed to the shape of the part (Ref 64). Restraint fixtures may require machined grooves, plugs, or clamps. Some straightening of parts can be accomplished in
aging fixtures by forcing and clamping slightly distorted parts into the fixture. The threaded fasteners for clamping should not be used because they are difficult to remove after heat treatment. It is preferable to use a slotted bar held in place by a wedge (Ref 64). The bore of a hub, the most important dimension in the hardening of thin spur gears, can be mechanically plugged to prevent the reduction of the bore and keep the out-of-roundness close to tolerance limits. When hardening large hollows, either restraining bands on the outside during tempering or articulated fillers serve the same purpose.

**Quenching Fixtures.** When water quenching or oil quenching is essential, distortion can be minimal by employing properly designed quenching fixtures that forcibly prevent the steel from distorting (Ref 88). Figure 14 shows a typical impingement-type quenching fixture. The requirements essential for the better design of this type of fixture are as follows (Ref 79):

- There must be an accurate positioning of the part in the fixture. Whenever possible, round bars should be rotated during quenching to level out variations in jet pressure around the part
- There should be an unhindered flow of quenchant through the sufficiently large holes (3.3 to 6.4 mm, or 0.13 to 0.25 in. in diameter). Jets as large as 12.25 mm (0.50 in.) in diameter may be employed with furnace-heated heavy sections (for example, plates). A large portion of the excess quenchant with these large jets is for the removal of scale (Ref 89)
- Spacing between the holes should be reasonably wide (for example, \(4d\), where \(d\) is the hole diameter)
- For oil-quenching fixtures, the facility to submerge the part is required to reduce fumes and flashing
- There must be the provision for efficient cleaning of the holes
- A facility must be available to drain out the hot quenchant for effective quenching performance with cold quenchant

**Fig. 14** A typical impingement-type quenching fixture. Source: Ref 80

**Pressure quenching** is the most efficient method of cooling parts from elevated temperature by using a combination of high pressure (such as 5 MPa, or 5 atm) and turbulent gas flow throughout the entire surface area of the workload (Ref 90). This is economical and fast, provides even cooling, offers a unique design and minimum distortion and improved metallurgical qualities. As a result of these beneficial effects this is suited to quench large-diameter tooling for the aluminum extrusion industry; quench larger-diameter carburized gear, larger fasteners, and precision gears to be jigged vertically; harden high-speed steel tools (such as saw blades, dies, and other parts with edge configuration) and 718 jet engine compressor blades (Ref 90). This is also employed to quench (vacuum processed) large sections of titanium alloy castings for aircraft applications (Ref 91). Figure 15 is a pressure-quench module that may be attached to vacuum-sealed quenched and continuous-vacuum furnace as a replacement for the oil-quench section.
Press quenching is widely employed in preventing and controlling quench distortion in components where the geometry renders them particularly prone to distortion (Ref 92). For example, flat circular diaphragms of spring steel used in the control or measurement of pressure are press quenched between two copper blocks, which cannot be accomplished by direct quenching (Ref 80).

Rolling Die Quenching. A rolling die quench machine can provide uniform water quenching with minimal distortion for large-production runs. When a heated part is placed on the rollers, the die closes and the rolls turn. This removes any distortion incurred during heating. According to manufacturers of rolling die quench machines, symmetrical parts with the following straightness can be achieved in production:

\[
TIR = K \frac{l}{d}
\]

(Eq 2)

where \(TIR\) is the total indicator reading of straightness, \(l\) is the length (in.), \(d\) is the diameter (in.), and \(K\) is the constant = 10\(^{-4}\).

For minimum yield strength requirements of 310 MPa (45 ksi), air-hardened or normalized parts with negligible distortion can be produced (Ref 79).

Stress Relieving. The presence of residual stresses in the parts caused by cold working, drawing, extrusion, forging, welding, machining, or heading operations greatly increases the tendency of distortion. However, these residual stresses can be relieved by subcritical annealing or normalizing treatment just before the final machining operation, which decreases the distortion to an appreciable extent. This is of special importance for intricate parts with closed dimensional tolerances (Ref 80). Stress reduction is necessary to avoid distortion during hardening and to avoid cracking resulting from the combination of residual stress to the thermal stress produced during heating to the hardening temperature. In the event that stress relieving is not performed after heat treatment, large distortions of the part can be removed by heavy grinding. However, the drawbacks of this operation are: possible elimination of most, if not all, of the hardened case of the carburized and hardened part; and danger of burning and crack formation on the surface layers. Hence, it is customary to stress relieve plain carbon or low-alloy steel parts at a temperature of 550 to 650 °C (1020 to 1200 °F) (for 1 to 2 h),...
hot-worked and high-speed steels at 600 to 750 °C (1110 to 1380 °F), and the heavily machined or large parts at 650 °C (1200 °F) (for 4 h) prior to final machining and heat-treatment operations. Subresonant stress relieving may also be employed to neutralize thermally induced stress without changing the mechanical properties or the shape of the component. These components include: large workpieces, premachined or finish-machined structural or tubular, nonferrous, hardened, nonsymmetrical or varying section thickness, stationary, or assembled. However, this does not work on copper-rich alloys and the edges of burned plates (Ref 93).

**Control of Distortion**

In order to remove or minimize distortion, the modern trend is to shift from water-quenching practice to milder quenching, for example, oil quenching, polymer quenching, martempering, austempering, or even air-hardening practice. Milder quenchants produce slower and more uniform cooling of the parts, which drastically reduces the potential distortion. Other strategies of controlling distortion for age-hardening aluminum, beryllium, and other alloys include: alloy and temper selection, fixturing, age-hardening temperatures, proper machining, and stamping operations (Ref 94). The fewer the number of reheats applied to components in case-hardening steels following carburizing, the smaller is the distortion on the finished part. When top priority is given to minimum distortion, it is desirable to make the parts from oil-hardening steels with a controlled grain size and to harden them by martempering direct from carburizing. Presently polyalkylene glycol-base quenchants, such as UCON quenchants HT and HT-NN, are variously used for direct quenching from the forging treatment, continuous cast quenching, and usual hardening of forged and cast steels and cast iron. In this case boiling does not take place at the component surface but rather at the external surface of the deposited polymer film. More uniform cooling occurs, and thermal stresses are released. Because of the lower boiling point and high thermal conductivity, UCON quenchants act through the martensite zone more rapidly than oil (Ref 95).

Distortion during ferritic nitrocarburizing is minimal because of low treatment temperature and the absence of subsequent phase transformations (Ref 66). There are many methods of reducing distortion in induction-hardened components; these methods are usually found by experience with variables such as the hardening temperature and the type and temperature of quenching medium employed. Methods of reducing distortion in induction-hardened parts include: the hardening of small spindles held vertically in jigs; the plug-quenching of gears to prevent the bores from closing in; the flattening of cams by clamping them together during tempering; and the selective hardening of complex shapes (Ref 96).

As a replacement of medium- or slow-quenching oils, UCON quenchants E and E-NN can be readily used in induction- and flame-hardening operations, both in spray and immersion types, for high-carbon and most alloy steels and traditional hardening of cast iron and cast or forged steels of complex geometry with better distortion-reduction properties. Agitation of quenchant should be carried out by motor-driven stirrers to move the medium with respect to the part being quenched or by pumps that force the medium through the appropriate orifice. Alternatively, the parts are moved through the medium, and for some applications, spray quenchant is recommended. Water additives are sometimes employed in salt baths to increase heat extraction (Ref 64).

Ultrasonic quenching is also effective in controlling distortion, which involves the introduction of ultrasonic energy (waves with a frequency of 25 kHz) in the quenching bath. This breaks down the vapor film that surrounds the part in the initial stages of water or oil quenching (Ref 86).

**Distortion after Heat Treatment**

**Straightening.** When every possible case has been employed to minimize distortion, it may still be essential to straighten after heat treatment, which has already been discussed.

**Grinding after Heat Treatment.** In the case of carburized or nitrided parts, the metallurgist and designer, together with the production engineer, must collaborate regarding the amount to be removed by grinding after heat treatment. This grinding allowance must be taken into account when determining the initial dimensions and also when specification for the case depth is to be applied.

Distortion may also occur after heat treatment, with time, owing to the completion of any unfinished transformation or the effect of increased temperature during grinding. For example, fully hardened components such as blade shears may be damaged by characteristic crazing pattern because of heavy and careless grinding. Local overheating results in the transformation of undecomposed austenite, and the accompanying changes in volume produce sufficient stresses to cause cracking and developing of a crazing pattern.
Dimensional Stability. To achieve dimensional stabilization or stability (that is, retention of their exact size and shape) over long periods, which is a vital requirement for gages and test blocks, the amount of retained austenite in heat-treated parts must be reduced because retained austenite slowly transforms and produces distortion when the material is kept at room temperature, heated, or subjected to stress. Dimensional stabilization also reduces internal (residual) stress, which causes distortion in service.

Stabilization can be obtained by multiple tempering (with prolonged tempering times); the first tempering reduces internal stress and facilitates its transformation to martensite on cooling. The second and third retempering reduce the internal stress produced during the transformation of retained austenite.

It is the usual practice to carry out a single or repeated cold treatment after the initial tempering treatment. In cold treatment, the part is cooled below the $M_f$, which will cause the retained austenite to transform to martensite; the extent of transformation depends on whether the tool part is untempered or first tempered. Cold treatment is normally accomplished in a refrigerator at a temperature of -70 to -95 °C (-100 to -140 °F). Tools must be retempered immediately after return to room temperature following cold treatment in order to reduce internal stress and increase the toughness of the fresh martensite. Finally, they are ground to size. It may be pointed out that vibratory techniques are being used more frequently to achieve dimensional stability but do not offer any metallurgical benefits (Ref 80).

Distortion and Its Control in Heat-Treated Aluminum Alloys

The high levels of residual stress and distortion that are produced in the water-quenched aluminum extrusion and forgings (such as 2000, 6000, and 7000 series) and aluminum castings can be reduced 60 to 100% by using proper selection of polyalkylene glycol quenchant or polyvinyl pyrrolidone 90 concentration (for example, 25% solutions for wrought alloys, 20 to 30% UCON quenchant A for thicknesses up to 25 mm (1 in.), and 17 to 22% for larger than 25 mm (1 in.) section thicknesses in casting alloys) with sufficient agitation, lower bath temperature, proper fixture (throughout solutionizing, quenching, and age-hardening treatments), and straightening (in the as-quenched state after taking out from the fixture) procedure. The initial cost of these polymer solutions as a replacement to the conventional hot-water quenching method is easily compensated for by other advantages such as reduced scrap, reduced machining (compared to two machining operations required--one before and another after heat treatment--in the conventional water-quenching method), and increased fatigue life as a result of reduced convective heat transfer or film coefficient between the part and the quenchant, more uniform quench, precise control of quench rates, and improved heat-transfer qualities from the deposition of liquid organic polymer on the surface of the part being quenched (Ref 97, 98, 99). This method costs less, therefore saves time and allows easy shaping, bending, and twisting of the parts without establishing residual stresses. Such parts as leading edge wing skins, spars, and bulkheads are used in the aerospace industries (Ref 96).

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Importance of Design

The wrong design of the tool material may result in the establishment of nonuniform heating and cooling of the components, which produces overload and/or internal stresses leading to distortion and failure during or after hardening. Correct consideration at the design stage plays an important role in lessening the distortion and danger of cracking. The basic principle of successful design is to plan shapes that will minimize the temperature gradient through the part during quenching. Fundamental rules such as maintaining a simple, uniform, regular, and symmetrical section with comparatively few shape changes, ensuring small and smooth cross-sectional size changes, and using large radii are still too frequently overlooked at the design stage. Thus, successful heat treatment demands a rational design that avoids sharp corners as well as sudden and undue changes of section.

It is often possible for tool designers to compensate for size distortion. For example, in preparing precision hobs for gear cutting, dimensional accuracy must be kept within very close tolerances. On linear longitudinal growth, it is the general practice to go out-of-round in the following high-speed steel bars as much as 0.3% in M1 type, 0.2% in M2 type, and 0.15% in T1 type during heat treatment. These data will alter slightly with changes in design of the hobs, but essentially the growth in tungsten-base high-speed steel is lower than that of the molybdenum-base high-speed steel (M1 and M2). This does not require any difficulty if the growth is compensated for and if the steel is consistent in its growth (Ref 87).

The distortion produced in the surface hardening of long shafts by the scanning method can be a great problem if the equipment is not in very good condition. Due consideration must be given so that locating centers run concentrically, in line and at the appropriate speed; the coil must be accurately aligned, and the quench must be correctly designed with sufficient number of holes of suitable size and angle. For long shafts with a relatively small diameter (for example, half-shafts, which are likely to distort), the use of hydraulically operated restraining rolls usually overcomes this (Ref 100).

The designer should bear in mind the following rules while designing a die or machine part that is to be heat treated:

- Distribution of the material should be as uniform as possible
- Provide fillets (large radii) at the base of keyways, cutter teeth, and gear teeth to avoid stress concentration; semicircular keyways, which permit the use of round-cornered keyways, are the right
choices. Ideally, drives using involute splines are preferred over keyways

- Avoid abrupt changes of section; in other words, provide smooth changes of section
- Large holes (such as drawing or cutting openings in die rings or plates) must be centrally located from the outer contour. In some cases holes are drilled through the heaviest section of the tool in order to help fairly balance the weight of the section rather than to unbalance it (Ref 64). Deep blind holes should always be avoided because they cause nonuniform quenching. If this is not possible, the hole can be ground in after hardening. Drilled hole junctions in a steel part should be avoided because they enhance very high and undesirable cooling conditions. The problem with these cross holes is to get sufficient quenchant in them. The inside surface of the holes tends to be in a state of high tensile stress, usually leading to cracking, at least with water quenching. As a minimum, the corner at the junction of the holes with outer diameter of the part should be given a generous radius to better distribute the tensile stress (Ref 90). Similarly, grooves and keyways in highly stressed areas should be avoided, or, if possible, they should be located in low-stressed areas of the part. Alternatively, fixtures should be used that make it possible for the hole or the inside of the groove to be quenched in the beginning or more rapidly than the rest of the part (Ref 24)
- Round off all the holes, corners, and outer edges
- If sharp corners are unavoidable, provide relief notches in place of sharp edges
- The insertion of identification marks on the hardened component is recommended, preferably after hardening with tools having well-rounded edges and minimum deformation (shallow penetration depth), and at positions far away from the high-stress concentration zones (reentrant angles, bends, and so on) (Ref 101)
- Large intricate dies should be made up in sections, which frequently simplifies heat treatment (Ref 64)

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Statistical Process Control of Heat-Treating Operations


Introduction

As demand for increased quality and documentation is felt by heat treaters, the subject of automatic collection and use of process information in a statistical process control/statistical quality control (SPC/SQC) format becomes increasingly critical. Data acquisition and documentation 10 years ago meant a chart recorder for temperature and a log sheet for the operator's dew-point readings. Today, it more than likely means a computer system tied into key points on the heat-treating equipment with the objective of logging important information for later review or perhaps being taken into account in real time.

Traditional versus Statistical Control
When man first heat treated a sword made from an iron carbon alloy, he learned that it was necessary to heat it until it glowed red and then plunge it into water. He further learned that the resulting product was often very brittle but could be made more usable by heating it again, this time to a much lower temperature. This small body of knowledge was enough process control to produce many useful products for many years.

Initially, it was noticed that if certain temperature ranges were used in certain circumstances, products of better quality would result and the idea of controlling temperature was born. Much later it was discovered that control of the carbon content of the material was important. Modern science was now controlling the properties of the end product.

If the tools used for process control in heat treating today are viewed against this backdrop, our current position on the evolutionary ladder can be pinpointed:

- **Step 1**: Rudimentary process knowledge from direct observation
- **Step 2**: Understanding of certain obvious influences from experimentation
- **Step 3**: Manual control of obvious influences like temperature
- **Step 4**: Automatic control of these obvious influences
- **Step 5**: Documentation of continued variation in process results, using statistical techniques to manually identify special problems
- **Step 6**: Use results of statistics and enhanced process understanding to gain control of the less obvious influences
- **Step 7**: Control the process from a theoretically complete model, taking into account all possible influences to produce a near-perfect product every time

The state of the art is currently at Step 5, the application of statistics in the search for problems. The jump to Step 6 is being made in some manufacturing disciplines using a new technique called "design of experiments." This is a complex statistical approach that may incorporate artificial learning into data regression-based computer programs. A program of this type will direct the human operator to perform experiment after experiment with a process in order to gain insight into any possible effects, direct or synergistic, that an entire list of possible process parameters might have. A process model initialized with known theory, but ultimately based on derived statistics, will emerge that can be used to indicate those parameters that will make significant contributions and should therefore be subject to automatic control.

A model such as this could be used to bake a better cake, for example. The model might direct the operator to make a cake with 1 egg the first time, 0.5 eggs the second, and 1.5 eggs the third. It would then ask for quantified results as to the measured quality of each of the experimental cakes. The model might conclude by saying that the optimum cake must be made with between 1.1 and 1.2 eggs, along with similar odd amounts of all the other applicable ingredients. It might even conclude that no salt is necessary in a cake because the statistics did not bear out importance of this item.

**Basic SPC/SPQ Nomenclature**

The purpose of this article is to provide a practical discussion of the application of SQC techniques to heat-treating operations and for that reason many of the applicable definitions and equations are not used but can be found by the reader in other reference materials on this subject. However, it is felt that the following minimum basic definitions and equations are necessary to be presented here for a better understanding of the text.

- **Accuracy versus precision**: Accuracy is measured by the extent to which the measured average of a group of readings, regardless of how widely the readings are dispersed, agrees with the true value of the unit being measured. Precision is the repeatability of the measurement (how much dispersion exists between readings) regardless of how close the readings are to the true value (or how accurate the readings are)
- **Gage repeatability and reproducibility study (GR & R)**: A study conducted on measurement devices to determine the precision and accuracy of the device. Results are expressed as an R & R index
- **Process**: Any specific combination of machines, tools, methods, materials, and/or people employed to attain specific output in a product or a service. A change in any one of the constituents results in a new process
- **Process capability**: Refers to the reproducibility of a process over a long time period during which
normal changes in workers, material, and other conditions are encountered

- **Quality**: Product features which are free from deficiencies and thus meet the needs of the customer and provide product satisfaction
- **Statistical process control**: The application of statistical techniques for measuring and analyzing the variation in processes
- **Statistical quality control**: The application of statistical techniques for measuring and improving the quality of processes and products. Statistical quality control includes statistical process control, diagnostic tools, sampling plans, and other statistical techniques
- **$C_p$ index**: Stands for capability of process, and is the ratio of the specification tolerance to six standard deviations ($6\sigma$). $C_p$ is a measure of the dispersion of data only
- **$C_{pk}$ index**: A measure of both dispersion and centeredness of the data as follows:

$$C_{pk} = \text{the lesser of:} \quad \frac{\text{USL} - \text{mean}}{3\sigma} \quad \text{or} \quad \frac{\text{mean} - \text{LSL}}{3\sigma}$$

where USL is the upper specification limit, and LSL is the lower specification limit

**Use of Statistical Control in Heat Treating**. In the last few years, it has become commonplace to see heat treaters tracking the results of their most critical processing with SPC techniques. The most commonly examined parameters include hardness, case depth, and distortion, although many others are tracked as well. Unfortunately, it has also become commonplace to observe these very same heat treaters failing to use these techniques for anything more than supplying required after-the-fact documentation on treated parts. It seems that the promise of statistical process control and its role in the revitalization of manufacturing quality in heat treatment is not being fulfilled.

It is important to understand that any SPC program is a means, not an end. Statistical process control is a tool to audit a process and help distinguish controllable variables from uncontrollable variables. It also provides a means for quantitatively measuring the level quality of a process. Statistical process control alone does nothing to improve the process. Continual improvement of the heat-treating process is the real goal and this comes from actions taken by people. Statistical process control is utilized as a tool to direct those actions.

Simply installing an SPC system on a dilapidated furnace does not improve the performance of the furnace. SPC alerts the furnace operator to the fact that, statistically, a problem does exist and requires investigators to determine which variables are causing excessive variations to occur. Statistical process control does not tell what is wrong, only that, statistically, excessive variation is present and this condition should be investigated to determine the assignable cause.

**SPC versus SQC**. It is necessary to make a distinction between statistical process control and its relative, statistical quality control. The latter is what most heat treatment shops are really using when histograms, mean/range charts, and capability indices are calculated for the variation in attained results (for example, hardness, case depth, and so on) in the processing of a given component.

Because statistical quality control is an after-the-fact tool, its best use is in the control of continuous processing where trends can be noticed and corrected before significant damage occurs. Processes such as large volume induction hardening (see the article "Induction Heat Treating of Steel" in this Volume) and continuous carburizing have been substantially improved with SQC charting techniques.

In batch processing, however, statistical quality control is of little value in preventing problems because at least one entire load of parts will be adversely affected before a problem can even be noticed. Even if the problem is caught after one load, the proposed solution cannot be tested without committing yet another load. Statistical quality control can be very helpful in batch or short run type (set-up dominated) processes by using it to analyze set-up variables. If the process is then set up to optimal set-up parameters (as determined by experimentation or evaluation of part outputs), meeting parts specifications will necessarily result.

**Statistical Process Control**. The idea behind true statistical process control is that the results of a process can be guaranteed if none of the relevant process parameters are allowed to stray outside of previously established control limits.
The long standing problem in applying statistical process control to heat treatment has been finding methods to quantify and measure process parameters that are of known importance (outside of the obvious ones). Many SPC programs are based upon charting controlled parameters such as temperature, atmosphere carbon potential, quenchant temperature, and so on. While this approach is certainly not incorrect, it does often lead to a situation where a deviation in an SQC chart (results) commonly cannot be attributed to any special cause deviation in a corresponding SPC chart (processing parameters), because all the things being charted are controlled variables that by design will not normally change.

**Processing Methods Considerations**

Repeatability is a key issue when considering how to improve a heat treatment process. The more process variables that can be controlled within specific known limits from part to part, furnace load to furnace load, and day to day, the more repeatable the process results will be.

**Continuous Operations.** The continuous types of heat treatment equipment (that is, rotary retort, pusher carburizers, belt furnaces, and so on) offer the most straightforward approach to applying SQC and SPC techniques to improve process performance.

Because a high volume of work pieces is involved, there is adequate opportunity to perform in-process sampling of key product characteristics. Negative outcomes can be predicted before they take their full course. Also, special causes are often more identifiable because process variables are steadier in continuous processes than in batch-type processes.

**Single Part Treatments.** With induction and flame heat treating, parts are typically processed one at a time. Using part evaluation techniques to predict negative results becomes difficult and impractical. Thus, the focus must shift to statistical process control and the identification, monitoring, and controlling of the process variables to ensure repeatability of the results.

Electric power, flame temperature, scan speed, coil dimension, part positioning, and quenchant temperature are some variables that need to be considered. Trending of process variables can be used to determine special causes.

**Batch Operations.** Batch-type furnaces usually offer the opportunity to do a significant amount of sampling and analysis within a load. However, all this does is develop a degree of confidence on the results of the entire load. The process variables must be monitored and analyzed to ensure that the process is under control and there is repeatability from load to load and from day to day. This is especially true when each load is different in terms of part geometry, material and/or specification, which is the norm in commercial heat treating.

**Process Deterioration**

A fact of life in any heat-treating process is that the equipment gradually succumbs to the wear and tear of constant operation, thus the process inevitably gets worse with time. The challenge is to counter this natural deterioration with corrective action before out-of-specification parts are produced.

SPC techniques can be utilized to measure furnace performance and address process deterioration in heat treating. By monitoring key process variables and/or key process outputs, preferably in on-line fashion, trends can be spotted and action taken before nonconforming product is produced.

Key process variables may mean not only controllable variables, but also uncontrollable and secondary variables.

**Uncontrollable Process Variables.** Examples of uncontrollable variables that are useful in the monitoring of a heat-treating process are:

- **Quench transfer time:** Although this is not a controllable variable in most furnace systems, it is often a critical parameter in terms of producing good parts. It may be beneficial to monitor and analyze transfer time in order to get an early warning of the deterioration of the transfer mechanism. One method for verification of sufficiently fast transfer time is to compare the maximum allowable transfer time for a successful process to the actual transfer time which would trigger an alarm if the maximum were exceeded. This automatic control method would then flag suspect loads or parts resulting from either a mechanical failure or equipment function deterioration.
• **Temperature recovery time:** By measuring and analyzing the time it takes for a batch furnace to reach setpoint temperature (with a standard load weight or empty), trends can be picked up that would indicate a loss in furnace performance. These out of control trends as plotted on an SPC chart would then trigger an investigation to determine the cause of the condition (for example, damaged insulation, poor door seals, heating system malfunction, and so on)

• **Quench temperature rise:** Although a quench system may be controlled within a specific range (that is, 30 to 65 °C, or 90 to 150 °F), it may be important to know how the temperature cycles from quench to quench. This would give a macroanalysis of the entire quenching system and give warnings of failed, or impaired, agitation and/or quenchant cooling. Over-loading of the furnace could also be indicated

**Secondary process variables** are those that are caused by the deterioration of control loops. Examples are of secondary variables:

- **Fuel consumption:** By monitoring gas or electric consumption for a standardized furnace cycle and loading (could be empty), diminished performance in the heating system can be detected
- **Additive atmosphere gas:** By monitoring and trending the amount of natural gas (or propane) addition required to control a specific carbon potential setpoint, the deterioration of furnace atmosphere integrity can be detected

**Process and Product Capabilities**

Capability studies are conducted on all types of manufacturing processes to determine the statistical variation of a product with respect to a measured characteristic. For heat-treating processes, characteristics frequently measured are hardness and case depth. Because these metallurgical characteristics are sometimes difficult to define, specifications may initially need to be clarified with regard to the exact test scales or test methods to be used and the critical locations where these tests are to be made before a capability study is conducted. Process results for many metallurgical and heat-treating processes are dependent on material-related characteristics such as hardenability, material chemistry, and/or part geometry that also make the process test results sensitive to those variables.

After the metallurgical requirements are clearly established, a basic process capability study may be conducted. Care should be taken so that the parts tested are from the loading locations representing the extremes in process variability. A good guideline for test sample locations is to use those loading locations prescribed for temperature uniformity surveys in specification MIL-H-6875.

For continuous processes, it is important to collect the samples over a sufficiently long period of time in order to reflect process heating power fluctuations or other process abnormalities that could be time dependent.

The use of normal probability paper for data representation and plotting is highly recommended. If the data does not plot as a straight line indicating a normal distribution, a metallurgical or process-related reason for this skewness should be apparent or be determined. An example of a capability study of an atmosphere harden and temper operation for automotive seat belt parts made from SAE 4037 steel is shown in Fig. 1 and Fig. 2.
**Fig. 1** Final hardness distribution analysis for a typical quench and temper operation
Fig. 2 Normal probability plot of data from Fig. 1. (a) Frequency distribution. (b) Distribution analysis sheet. Specification, mean = 35 HRC; range = 7 HRC. Results, mean = 35.7 HRC, $6\sigma = 5.5$ HRC, $C_p = 1.27$. Action, adjust temper to adjust mean to 35 HRC

As can be seen in Fig. 3, the overall process capabilities results are the result of many contributing factors:

- **Base material contributions**: Unique material characteristics, material defects, and hardenability differences. These can vary from lot to lot and also between materials
- **Part-related contributions**: Part geometry and section size variations
- **Process-related contributions**: Temperature uniformity as affected by process control and mass effects, time control, atmosphere control, and cooling method (as determined by uniformity and average severity)
- **Evaluation method contribution**: Standards accuracy and testing method accuracy
Thus, to successfully use the process capability study as a dynamic tool to refine and narrow process variability, the following three steps should be used in conjunction with process capability studies:

**Step No. 1:**
- Identify critical control variables and their relative contributions to process attribute variations (this can be done by process modeling techniques)
- Measure process inputs with corresponding process output results
- Document process control procedures

**Step No. 2:**
- Modify control procedures, manufacturing procedures, or equipment in order to reduce process variability

**Step No. 3:**
- Remeasure process capability (as in Step No. 1 above) to ascertain the effectiveness of the changes

The overall heat-treating process variability result may be characterized as being comprised of the following factors (they may be classified into four categories) and the accompanying sources of the undesirable background signals (intrinsic or extrinsic noise):

- Base material related (intrinsic noise)
- Part configuration and manufacture related (intrinsic noise)
- Process related (extrinsic noise)
- Evaluation method related (extrinsic noise)

By using properly standardized test coupons as the basis of a process capability study, we can separate out the variability due to intrinsic noise factors and arrive at the inherent process capability. However, in practice, we will still have these contributions in the process and this should be kept in mind. Additionally, a GR & R study may be performed on the evaluation method to determine the contribution of these factors to variability.
**Base Material Considerations**

Cast irons are probably the best example of a material where test results (that is, hardness) can be a function of the hardness testing scale used. This sensitivity of hardness value to the testing method and the hardness scale used is because the different phases present in the workpiece vary significantly in hardness. This same effect exists in other materials which are heat treated (see Fig. 4).

![Fig. 4 Microstructure of hot-rolled AISI 1022 steel showing severe banding. Bands of pearlite (dark) and ferrite were caused by segregation of carbon and other elements during solidification and later decomposition of austenite. Etched in nital. 250×](image)

Another type of problem that can influence testing results which are not the direct result of processing is "banding." Many steels, particularly a resulfurized one such as AISI 1100 or 1200 series, exhibit banding or microalloy segregation. The bands exist prior to heat treatment and the ferrite-rich and pearlite-rich areas run in bands across the longitudinal rolling direction of the bar stock from which parts are made.

It has been found that this condition can result in a 4 to 10 point of Rockwell C hardness variation after hardening between these bands of different chemical composition. This problem is greatest when the bands are widest and the heat treatment times are very short, such as for induction hardening processes.

**Decarburization.** Surface carbon reduction to a greater or lesser degree exists on most steels having more than 0.30% C. This defect results from basic steel manufacturing and if not removed in the part manufacturing process prior to heat treatment can influence the surface hardness of parts after induction, flame, or direct hardening processes that may not be capable of correcting the surface decarburization condition. However, it should be recognized that many heat-treating processes can also cause this same problem. It is thus important for one to have characterized the incoming product to be processed so that the controllable incoming material variability can be isolated and corrected independently from the product variations due to the process.

**Material Variations.** Before applying statistical control techniques to monitor process or product uniformity, it is important to understand how the raw material uniformity is controlled prior to heat treat processing. That is, whether or not the incoming material is identified and kept separate by heat numbers in the case of steel or by batch number in the case of cast materials.

**Part-Related Contribution**

Each part evaluated by statistical means after heat treat processing can have other unique features such as section size variation, geometry, and/or surface finishes which can affect the test results obtained.

**Use of Test Coupons.** Test coupons can be used to provide an accurate heat-treating process evaluation if one is only interested in measuring changes or variations in the process. Test coupons must be carefully designed to be an effective statistical process control tool. They must be:
• Properly selected for size, shape, and material that can be directly correlated to the material and parts configuration being processed
• Prepared in sufficient quantity (same heat of steel) and quality to eliminate or minimize the material uniformity variable from the processing variation

By using statistical quality control with test coupons in conjunction with statistical quality control on heat treated parts, product variations attributed to process only variations may be identified and controlled.

**Example 1: Use of 10 000 Test Pins Measuring 64 mm (2 1/16 in.) Long by up to 17.8 mm (0.700 in.) OD Made from a Single Heat of 8620H Steel Used to Monitor the Carburizing and Hardening Operations of 5- to 8-Pitch Gears.**

Test pins were used to monitor carburizing and hardening processing for 5- to 8-pitch gears made mostly from 8620H steel. This procedure is used to monitor the process variation in carburizing of surface hardness, effective case depth, and core hardness. The diameter chosen for the test pin is based on the gear tooth thickness and the fact that the test pin center cooling rate would be on the steeper portion of the Jominy hardenability curve. This means that monitoring the center core hardness on test pins is an indirect measurement of quench uniformity.

**Purchase and Processing of Test Pins.** The minimum quantity of test pins purchased was 10 000 pieces from a single heat of 8620H. The OD of these pins were ±0.13 mm (±0.005 in.) for a given lot of pins with the absolute size being 12.7 to 17.8 mm (0.500 to 0.700 in.). The length was 64 ± 1.6 mm (2 1/2 ± 1/16 in.). A groove was added to the pin for attaching the pin by wire to the load.

At least one test pin is processed with each batch load or one pin is run every 4 h on each row of all continuous furnaces.

Test pins were hung in all furnace loads in a location where the processing was typical of the parts processed.

The test pins are evaluated as-quenched only. *No tempering is permitted.* Test pins evaluated for purposes of SQC control were from pure cycles with no abnormal changes in times, temperatures, or quench procedure.

**Testing Procedures for Test Pins.** File the surface of the pin to check for file hardness and to make a smooth surface. Check three hardness readings on Rockwell C scale and record the average. Do not use V anvils but use flat or spot anvil only.

Cut parallel section 6.4 mm (1/4 in.) thick from the center of the test pin. Set the diamond and anvil by checking at mid-radius. Check the center hardness by Rockwell well C scale and record.

**Effective Case Depth.** On the section cut from above, grind the surface to be checked on a 120-grit or finer paper. Test from the surface in to the point where the hardness is 85.5 HR15N (50 HRC). Measure from the surface to the center of that mark using a Brinell glass. Record the reading as effective case depth in thousandths of an inch.

The referee method for checking effective case depth is by 500-g microhardness to 50 HRC equivalent. Therefore, at least one of every ten checks and/or any check of effective case depth not within the specified limits is to be verified by the microhardness method.

The results from above are to be plotted by cycle and furnace on the form shown in Fig. 5.
This method can be started and used on a monitoring basis only for a short time until mean values with upper and lower control limits can be established.

**Process-Related Contributions.** This is the most important characteristic to identify and control to reduce variability of the heat treated products. Exactly how to accurately control process parameters is covered in the section "Design of
Experiments” in this article. By using standardized test pins and modeling to separate processing parameters, the individual parameter contribution to a measured characteristic such as effective case depth can be shown as detailed in Table 1.

**Table 1 Contribution of selected parameters to variations in effective case depth for required 0.85 to 1.00% surface carbon level at 870 °C (1600 °F) processing temperature**

<table>
<thead>
<tr>
<th>Case depth</th>
<th>Variation in case depth for selected parameters, %&lt;sup&gt;(a)&lt;/sup&gt;</th>
<th>Temperature variation (ΔT)</th>
<th>Time variation (Δt)</th>
<th>Carbon variation (Δ C)</th>
<th>Atmosphere</th>
<th>Quench uniformity&lt;sup&gt;(b)&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>11 °C (20 °F)</td>
<td>28 °C (50 °F)</td>
<td>56 °C (100 °F)</td>
<td>5 min</td>
<td>10 min</td>
</tr>
<tr>
<td>0.51</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.020</td>
<td></td>
<td>6</td>
<td>14</td>
<td>33</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>1.02</td>
<td></td>
<td>6</td>
<td>16</td>
<td>34</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1.52</td>
<td></td>
<td>7</td>
<td>17</td>
<td>35</td>
<td>&gt;1</td>
<td>1</td>
</tr>
</tbody>
</table>

<sup>(a)</sup> Total process variation = \( \sqrt{A^2 + B^2 + C^2 + D^2 \ldots + Z^2} \), where A, B, C, D, and Z are % variations attributed to ΔT, Δt, atmosphere ΔC, quench uniformity ΔC, and additional variables, respectively.

<sup>(b)</sup> Variation in case carbon level when quenched to 50 HRC.

The most significant observation from Table 1 is that quench uniformity is an equally significant factor in the carburizing process with time, temperature, and atmosphere control as variables.

**Measurement Accuracy**

The most important reason for calibrating with traceable test blocks and indenters and using a stable hardness standard is the U.S. industry movement toward higher levels of statistical quality control.

Testing variables must be eliminated wherever possible to permit the production part process as much range as possible. This means keeping the tester, anvil, operator, indenter, and test block error to the smallest possible percentage of the production tolerance. Test block consistency is one very important controllable variable. Some test blocks state maximum variation of 0.2 hardness units down to 40 HRC. With ten standardizing tests on a larger, thicker block that show no greater variation than 0.2 hardness units, there is the likelihood there would be few readings found above that variation. Conversely, on a thin standardizing test block with five tests where one reading out of five may show a variation of 0.4 hardness units, there is the likelihood that there would be other 0.4 or greater measurement variations. When plotting \( \overline{X} \) - R control charts (see the article "Statistical Quality Design and Control" in Volume 17 of ASM Handbook, formerly 9th Edition Metals Handbook) where \( \overline{X} \) is the sample mean and R is the range, this greater test block variation over time could erroneously show the hardness tester is not consistently accurate within tight limits. The variation could lead to incorrect process adjustments or put into question the process capability. The higher consistency, more stable test block would show a tighter band of tester accuracy and repeatability performance.