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IntensiQuench^{SM} Process Theory and Applications

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IntensiQuench^{SM} Process Executive Summary

In this paper, IQ Technologies Inc presents a complete overview of intensive quenching processes, their applications and intensive quenching case studies to provide a better understanding of these effective quenching techniques.

The purpose of quenching steel parts is to achieve the desired metallurgical structure, usually hardened "martensite," while keeping distortion to a minimum. The heat treater must usually balance between the trade-off of hardness for distortion (or part cracking). Stated another way, the faster the steel part is quenched, the higher the "as quenched" hardness and the deeper into the part the hardness is driven, but also the higher the probability of part distortion or even cracking.

About 35 years ago, Dr. Nikolai Kobasko of the Ukraine discovered the "intensive quenching" phenomenon. Intensive quenching, known as IntensiQuench^{SM}, is an alternative way of hardening steel parts. IntensiQuench^{SM} processes can be defined as cooling ***usually with pure water quenchant or low concentration water/salt solutions*** at a rate several times higher than the rate of "normal" or conventional quenching. In contrast to the conventional heat-treating practices, intensive quenching calls for very high cooling rates for parts within the martensite phase. Dr. Kobasko's research shows that ***very fast and very uniform part cooling*** actually reduces the probability of part cracking and distortion, while improving the surface hardness and durability of steel parts.

The rapid cooling rate also provides greater hardened depth, which in turn improves part mechanical properties. It creates high residual compressive stresses on the part surface, allows the use of less alloy steels or making the part smaller (lighter), and yet stronger, and makes quenching process more cost-effective. In addition, IntensiQuench^{SM} is clean and environmentally friendly method since it uses plain water or low concentration water/salt solutions as a quenchant in contrast to traditional heat treatment practices that use usually hazardous, environmentally non-friendly oil.

Since his discovery, Dr. Kobasko and his colleagues conducted hundreds of laboratory and field validation experiments and developed computer models for intensive quenching technology. Applications of intensive quenching are already in routine use in many production heat-treating plants in countries of the former Soviet Union as well as in China and Bulgaria.

This paper describes in detail the following intensive quenching phenomena:

- Simultaneous formation of a strong martensitic structure throughout the whole part surface area creating a firm case or shell (in contrast to conventional quenching when martensite forms non-uniformly resulting in part distortion).
- Development of high compressive stresses on the part surface preventing the part from cracking and minimizing the part distortion (in contrast to conventional quenching that creates tensile surface stresses that may result in part cracking).
- Three intensive quenching techniques (IQ-1, IQ-2 and IQ-3) developed by Dr. Kobasko over the years.
- Intensive quenching process computer models that are a part of IQ Technologies Inc "know how" and are used for development of cooling recipes.
- Different types of intensive quenching equipment.

- Numerous examples of implementation of the IntensiQuench^{SM} process for medium and high carbon steels, alloy steels and tool steels.

The following benefits of the IntensiQuench^{SM} process were proven by a numerous experimental studies conducted by Dr. Kobasko and IQ Technologies Inc during the recent years:

- Increases the depth of hardness.
- Minimizes surface cracking.
- Minimizes part distortion.
- Achieves the same or better metallurgical properties while using lower alloy steel resulting in significant cost savings in material.
- Provides an optimum combination of high surface compressive stress; high-strength, wear-resistant quenched layer of optimum depth; and relatively soft but properly strengthened core resulting in longer part life.
- Fully eliminates or considerably reduces the duration of the carburization cycle.
- Uses less costly, environmentally friendly quenchant (usually plain water) instead of expensive hazardous oil, resulting in the significant reduction of the heat treatment costs and in cost savings from environmental waste stream management, cleaner plant, cleaner parts, lower insurance, better work environment, etc.
- Achieves the greater productivity of the quenching equipment since IntensiQuench^{SM} processes provide much faster cooling rate.

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IntensiQuench^{SM} Process Theory and Application

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1. The Basics of Intensive Quenching

1.1 Intensive Quenching Technology Theory

There are several different quenching techniques used in common practice today including direct quenching, time quenching, selective quenching, etc. The selection is based on the effectiveness of the quenching process considering the materials, parts, and quenching objectives (usually high hardness with acceptable distortion). In all cases, the quenching process is controlled to prevent a high cooling rate when the material is in the martensite phase. This rule is based on the belief that it will avoid high tensile, residual stress, distortion, and the possibility of part cracking.

Extensive research conducted in the Ukraine by Dr. Nikolai I. Kobasko has shown that avoiding a high cooling rate when material is in the martensite phase is not always necessary or optimal to obtain the best properties. His studies showed that a very high cooling rate within the martensite range would actually prevent quench cracking, if done correctly. This phenomenon was discovered first by laboratory experiments and then was supported by computer simulation (**References 1** and **2**). A large number of field experiments on a variety of steel parts validated both the theory and the computer simulation (**References 3** and **4**).

Figure 1 shows experimental data obtained for a cylindrical specimen made of a low alloy steel with a diameter of 6 mm (0.25"). The bell-shaped curve clearly illustrates the general effect of the cooling rate within the martensitic phase on crack formation: the probability of quench cracking is low for both slow and ***very rapid and uniform*** cooling, known as the IntensiQuench^{SM} process. The curve also shows that once quenching is in the "intensive zone" or above, the benefits of the IntensiQuench^{SM} process – high hardness *and* low distortion -- will be attained. One cannot quench "too fast" because once the surface temperature of the part reaches the quenchant temperature, the part simply cannot cool any more quickly; cooling is limited by the ability of the part to conduct the heat energy from the core to the surface. IntensiQuench^{SM} processes are robust.

1.1.1 Why Does the IntensiQuench^{SM} Process Minimize Cracking and Distortion? Imagine a steel part with a varying thickness (**Figure 2**). During conventional quenching, the martensite forms first in the thinner section of the part since this section cools faster and reaches the martensite range earlier than the thicker one (**Figure 2a**). The martensite specific volume is greater than the specific volume of the remaining austenite. Therefore, the thin section expands while the thick section of the part continues contracting due to cooling until it too becomes martensite. This creates stresses resulting in the distortion and possible part cracking.

Now imagine that the same steel part is cooled very rapidly and uniformly. In this instance, the martensite forms simultaneously over the entire part surface creating a hardened "shell" (**Figure 2b**). Dr. Kobasko's research showed that this uniform, hardened shell creates high compressive stresses resulting in lower distortion and lower probability of cracking.

1.1.2 Why Do Surface Compressive Stresses Occur? Imagine a cylindrical steel part. To simplify a mechanism of the stress formation in the part, let us assume that the part consists of only two sections: a "surface layer" and a "core." (It would be more accurate to consider the part as a series of concentric layers, like layers of an onion, where the heat and the phase transformation are "transferring" from layer to layer.) Now assume that the part's "surface layer" consists of a set of "segments" joined together by "springs" to form an elastic "ring" (**Figure 3**). When the whole steel part is heated above Ac_3 temperature before quenching there is no tension in the "springs" and there are no stresses between the "segments" (σ=0, see **Figure 3a**). During quenching, the surface layer cools rapidly resulting in the contraction of the "elements." To compensate for the contraction of the segments in the surface layer

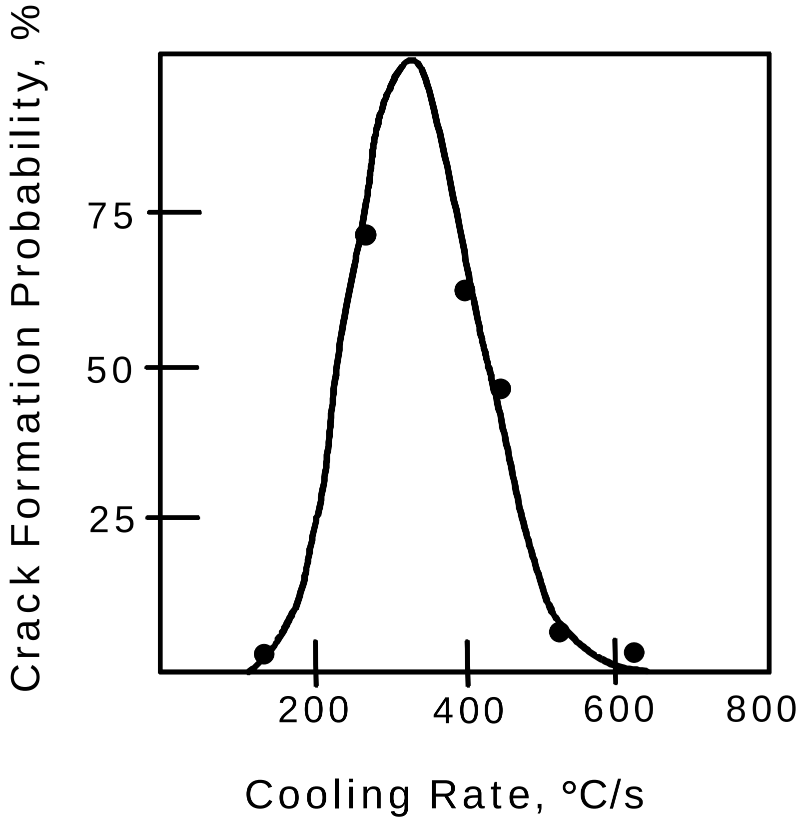


Figure 1 **Effect of Cooling Rate on the Probability of Cracking**

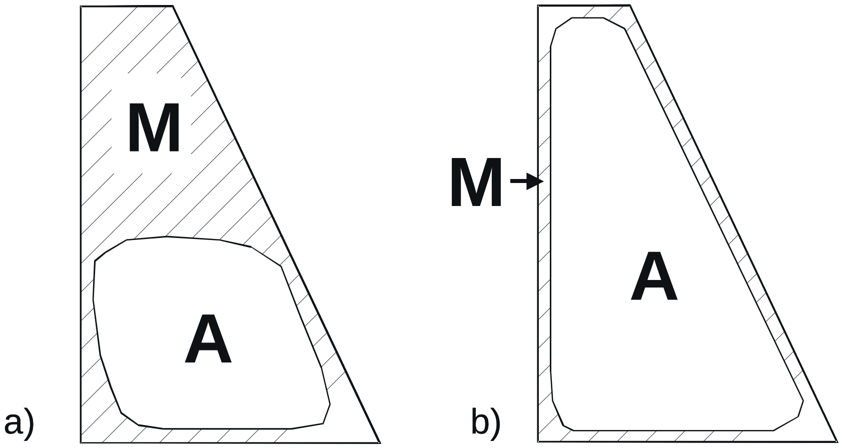


Figure 2 Martensite Formation During Drenching
a) Conventional quenching, b) Intensive quenching

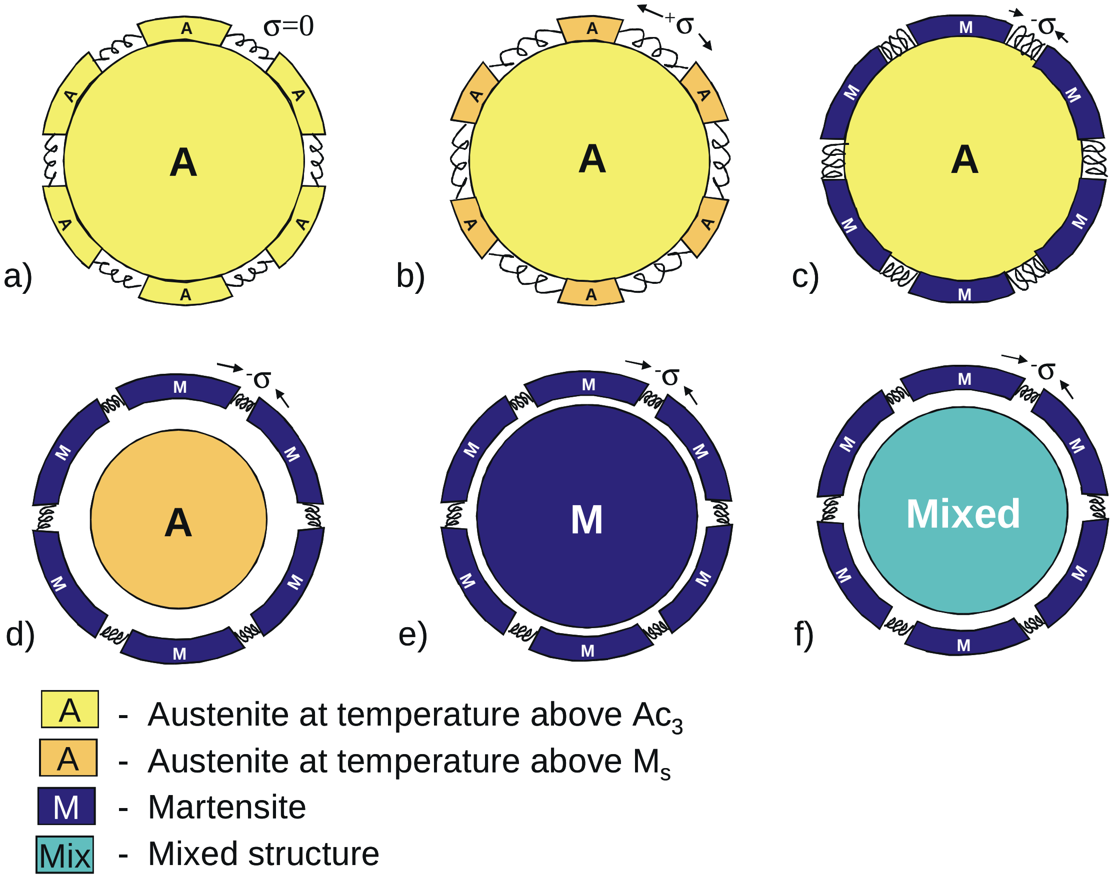


Figure 3 **Surface Stress Conditions During Intensive Quenching**

during cooling, the “springs” expand simulating the development of tangential (hoop) **tensile** thermal stresses (see **Figure 3b**).

When the surface layer reaches the martensite formation start temperature, Ms, the austenite in the surface “segments” transforms into martensite (see **Figure 3c**). The martensite specific volume is greater than the austenite’s. This results in the expansion (swelling) of the surface layer “segments”, causing the “springs” to contract. The contraction of the springs illustrates the development of surface **compressive** hoop stresses.

It is important to note that during intensive quenching, the part surface layer reaches the martensite start temperature M_s so quickly that the part core is still very hot (practically at the initial austenitizing temperature). (This is in contrast to conventional quenching, for example marquenching, when the part core temperature may be just above the M_s temperature at this period of time.)

While the martensitic structure is forming in the part surface layer, the part’s austenitic core continues to cool down to the M_s temperature, shrinking in size as it cools (**Figure 3d**). We call this core thermal contraction “pre-phase transformation shrinkage.” **As the core shrinks, the strong martensitic shell maintains the part’s initial size with low distortion – almost as though a “die” has been built on the outer shell of the part.** The shrinking (cooling) austenitic core draws the martensitic surface shell toward the part center increasing the surface hoop **compressive** stresses (with the “springs” between the surface layer “segments” contracting). Note that in a real quench the material does not “break” between the shrinking austenitic core and the fixed martensitic “shell” (as shown on **Figure 3d)**. This is because the hot austenite is in a “super-plastic” state; when stresses between the “surface” and “core” sections of the part exceed the austenite yield strength, the austenite deforms to maintain part integrity within the shell.

If intensive quenching continues further, then within a short time (in a matter of seconds), the martensite starts forming in the part “core,” resulting in the core swelling (see **Figure 3e**). The expanded part core pushes the part surface layer back from the part center resulting in diminution, but not elimination of the high surface compressive stresses. (Put another way, the distance between the surface layer “segments” increase, resulting in the expansion of the “springs” and the lowering of the compression in the surface shell). The surface residual stresses are still compressive even in a through hardened part because the size of the expanded, martensitic core is actually smaller than the size of the initial, hot austenitic core. In other words, the steel’s *pre-phase transformation shrinkage* (of the cooling austenitic core) offsets the following phase transformation *expansion* in the final, martensitic core.

At some point in time, the surface compressive stresses reach their maximum value. It happens just before martensite starts forming in the core. **The key element of the IntensiQuench^{SM} technique is to “interrupt” the rapid, uniform cooling of the part’s “shell” when compressive stresses in the part’s surface are at their maximum.** The “interruption” is done by simply removing the part from the intensive quench. As the cooling rate of the part “shell” slows, the part “core” will also begin cooling more slowly and the martensite phase transformation advance may slow or cease entirely if the part is thick enough (over approximately one inch). If the martensite formation ceases, the remaining austenite in the core transforms into intermediate phases, such as bainite, ferrite, pearlite, etc. (See **Figure 3f**). Since this mixed “core” structure has less specific volume than a “pure” martensite core (as discussed above), the quench results in a higher level of surface residual compressive stresses compared to the through hardened version (see **Figure 3e**). The precise time for interruption is predicted by the IQ Technologies computer software model. Usually, there is a window of several seconds to move from each stage of the intensive quench process; the thicker the part, the “bigger the window.” IntensiQuench^{SM} is robust and practical for production environments.

Curve I on **Figure 4** illustrates the dynamics of the "surface" stress conditions during intensive quenching over time with a "mixed core" and Curve II on **Figure 4** illustrate the dynamics of the "surface" stress conditions during intensive quenching over time with a "martensitic core" structure.

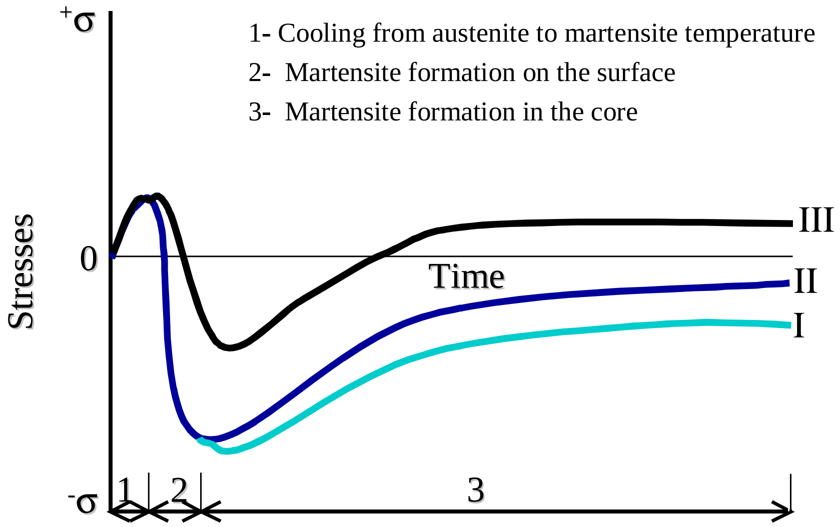
It is important to note that intensive quenching's creation of residual compressive surface stresses, even when the part is through hardened, is in stark contrast to conventional quenching where residual surface stresses are usually tensile or neutral when the part in quenched through. This is because in conventional quenching the part core temperature is just above the M_s temperature when martensite starts forming in the part surface layer (**Figure 5a**). Pre-phase transformation shrinkage of the core in this case is negligible compared to intensive quenching (see **Figure 3d**) and it does not offset the subsequent core expansion. In non-intensive quenching, part core expansion is actually greater than the pre-phase transformation thermal shrinkage (**Figure 5b**). Therefore, after conventional quenching, the swelled core pushes apart the surface "segments" creating **tensile stresses** on the part surface (the "springs" between the "segments" expand, see **Figure 5b** and curve III on **Figure 4**). This is why many conventionally quenched parts are very "unstable" and may crack if not tempered soon after quenching.

In a "real" part, one with more than "a surface layer" and "a core," this phenomenon is repeated in layer after layer of the part until the entire part is cooled below martensite formation finish temperature, M_f. In actual parts, the austenite to martensite transformation takes place in a sequence of concentric layers much like layers in an onion (**Figure 6**). Once the "shell" is cool and is in compression, the intensive quench is "interrupted." Once the intensive quench is interrupted, the "layers" beneath continue to cool by conduction. Since heat conduction within a solid is very uniform and relatively fast, the uniform cooling of the part continues (even after the "interruption" of the intensive quench), resulting in a mixed structure in the part core with residual compressive stresses on the surface. Each concentric layer of the part goes through the same thermal *shrinkage* (from cooling austenite) and the same phase transformation *expansion* (from forming martensite or other hardened phases) until the part is fully transformed.

The intensive quenching phenomenon of high surface compressive stress in through hardened parts and in the parts with the mixed structure in the core is confirmed by the results of detailed computer simulations of part thermal and stress/strain conditions, and more importantly by experimental data and case studies (detailed in the later sections of this paper). Numerous laboratory and field experiments have shown that the strength of the final part is related to the speed of the quench (or the rate of external heat transfer). The increased strength and higher surface compressive stresses due to intensive quenching help to eliminate quench distortion and enhance the durability (service life) of machine parts and tools (**References 5** and **6**).

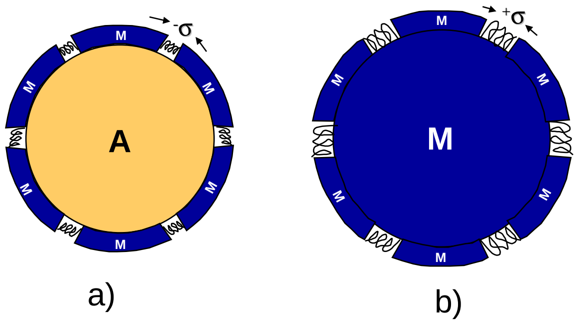
1.1.3 Optimum Hardened Depth. Dr. Kobasko's testing shows that the "optimum hardened depth" of the "shell" corresponds to the "maximum" compressive surface stress, and is a function of the part dimensions and part geometry. For best results from intensive quenching, the steel alloy (and its related "hardenability") should be selected for the part's geometry to ensure that hardening occurs to the optimum depth. The higher alloy or deeper hardenability steels are not always the best choice for intensive quench to create high compressive surface stresses and still be able to interrupt the quench at that point to slow the transformation of the core. Use of the intensive quenching computer model makes reaching the optimum depth a certainty.

For a steel with controllable hardenability, the IntensiQuench^{SM} method will provide an optimum combination of high compressive surface stress; high-strength, wear-resistance; quenched layer of optimum depth; and a relatively soft but properly strengthened core (**Reference 4**). A "carburized case" without the long "carburization" cycle. This combination is ideal for applications requiring high strength



I. Intensive quenching with mixed core structure
II. Intensive quenching with martensite core
III. Conventional quenching

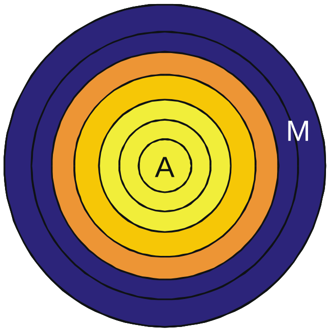
Figure 4 **Surface Stress vs. Time**



A - Austenite at temperature just above M_s

M - Martensite

Figure 5 **Surface Stress Conditions During Conventional Quench**



A - Austenite at temperature above Ac_3

A - Austenite at temperature between Ac_3 and M_s

A - Austenite at temperature just above M_s

M - Martensite

Figure 6 Part Structure Concentric Layers

and resistance to static, dynamic, or cyclic loads. Dr. Kobasko also demonstrated experimentally that by applying the intensive quenching method, the desired properties of the part could be obtained using less expensive steels (steels containing two or three times less alloying elements than conventional alloy grades).

Since water is the best intensive quenchant for its high heat-extracting index, another benefit of the intensive quenching process is the elimination of oil, salt and other potentially hazardous quenchants.

1.1.4 Modes of Heat Transfer During Quenching. To better understand different ways of how the IQ process can be realized let us consider the modes of heat transfer that take place during conventional quenching. Boiling of the quenchant on the part surface starts immediately after the part is immersed into the quench tank. The high heat flux from the part surface causes so high a rate of water evaporation that a vapor blanket (a vapor film) engulfs all or part of the part surface. This mode of heat transfer is called film boiling or shock/film boiling. The film boiling is a non-controllable process since the vapor blanket appears and dissappears sporadically throughout the part surface. Often, the vapor blanket covers the entire part surface for a certain period of time. Film boiling is the least uniform phase of quenching causing the most part distortion.

During the film boiling stage of cooling, the heat flux from the part surface decreases since the vapor blanket creates a high thermal resistance for moving the heat from the part to the quenchant. The decrease in the heat flux from the part surface results in the reduction of the water evaporation rate. At some point of time, the vapor blanket collapses and the film-boiling mode of heat transfer switches to the nucleate boiling stage.

During the nucleate boiling mode of heat transfer, tiny bubbles are forming at the rate of more than 50 per second. During this stage of cooling, the heat flux from the part surface first increases since there is no more vapor blanket around the part surface, and then the heat flux decreases, due to the reduction of the temperature gradient throughout the part cross-section. The heat transfer throughout the nucleate boiling stage of cooling is characterized by the highest value of heat extraction during the quenching process.

Eventually, the heat coming from the part subsides and cannot support quenchant boiling. At this point convection mode of heat transfer begins. Convection heat transfer is the slowest (least intensive) mode of the heat extraction during the conventional quenching processes.

1.2 Three Intensive Quenching Techniques

Over the years, Dr. Kobasko and his colleagues have developed three intensive quenching techniques known as IQ-1, IQ-2 and IQ-3 quenching methods. These three types of intensive quenching differ by modes of heat transfer on the part surface during intensive cooling:

- In IQ-1 quenching processes, film boiling and nucleate boiling are both present on the part surface.
- In IQ-2 method, the film boiling is absent and the main mode of heat transfer on the part surface is the nucleate boiling following by convection cooling.
- In IQ-3 technique, the intensity of cooling is so great that both film and nucleate boiling are completely absent, and the basic heat transfer mode is convection.

1.2.1. IQ-1 Intensive Quenching Method. The IQ-1 quenching method is a two-step cooling process. It is used for medium-alloy and high-alloy steel parts. At the first stage of quenching, steel parts cool slowly from the austenitizing temperature down to the martensite start temperature M_s (for example, in hot oil or in high-concentration water/polymer solutions). There is an insignificant temperature gradient throughout the part cross-section within this slow cooling stage. Therefore, the initial temperature throughout the entire part can be assumed equal to the temperature M_s at the beginning of the second stage of cooling.

The second stage of quenching is very intensive and it takes place within the temperature range of martensite transformations. Water jets or directed streams of quenchants around the steel part provide high cooling rates. Intensive cooling results in the formation of high compressive stresses on the part surface. These compressive surface stresses “fix” the low part distortion obtained in the first, slow cooling stage, and also provide additional strengthening or “super strengthening” of material.

However, a shortcoming of IQ-1 process is that a) oils or high-concentration polymers are used at the first stage of cooling, and b) the second stage of cooling is conducted in a separate chamber. The use of quench oils or high concentration of polymers in water (20% to 24%) considerably reduces the hardening capacity as a quenchant for steel parts. The necessity of a second cooling chamber complicates the hardening process and makes it difficult to maintain in practice and more expensive. A more advanced steel quenching method, IQ-2 has been developed to alleviate the shortcomings of IQ-1.

1.2.2 IQ-2 Intensive Quenching Method. The IQ-2 technique is a three-step procedure: a) fast cooling under quenchant nucleate boiling heat transfer conditions on the part surface, b) slow cooling in the air, and c) convection cooling in the quenching tank. In IQ-2 quenching method, the duration of a sporadic film-boiling stage is minimized to avoid part cracking and distortion. This is the main reason why the plain water is not the preferred quenchant in the IQ-2 process. Various low concentrations of mineral salts in water are effectively used to eliminate film boiling and stop part corrosion.

A water/salt solution eliminates film boiling as follows: The water/salt solution contains negatively charged ions. The heated part (at austenitizing temperature) is always positively charged. When the positively charged part is immersed into the quench tank the negative ions are attracted to the part surface. The salt ions together with quenchant flow physically destroy the vapor blanket. Note, that the quenchant flow velocity need not be as high as in IQ-3 systems (see Section 1.2.3 below). However, the agitation should be more intensive compared to conventional oil quench tanks.

During the first stage of cooling, martensite forms rapidly in the part surface layer. To avoid surface cracking in IQ-2, the fast cooling is interrupted when there is less than 50% of martensite formed in the surface layer of the part and the surface layer is still "plastic." The steel part is removed out from the quenchant. Note that the boiling point of the quenchant on the part surface should correspond to the temperature on CCT or TTT diagrams providing approximately 50% martensite.

After "interruption" of the intensive stage of cooling, the part cooling continues in the air. During this second stage of IQ-2, the part surface layer or "shell" is self-tempered by the heat coming from the hot core. The part temperature equalizes throughout the cross sectional area. Also, in this second stage, the part compressive surface stresses (developed in the first stage of cooling) are fixed. As a result of the self-tempering process, the martensitic surface layer strengthens eliminating possible cracking during final stage of the IQ-2 cooling. In the third phase of the IQ-2 quench, the part is returned to the intensive quench tank for further convection cooling to complete the required phase transformations in the surface layer and in the part core.

A shortcoming of the IQ-2 method is that the water/salt solution boiling temperature does not always coincide with the martensite finish temperature of the alloy. To avoid this shortcoming, an IQ-3 intensive quenching process was proposed.

1.2.3 IQ-3 Intensive Quenching Method. IQ-3 is the most intensive and best hardening method in terms of creating high compressive surface stresses, to an optimum depth; IQ-3 yields the highest amount of "super strengthening" of the part for a given material or alloy. Simply stated IQ-3 gives the most "bang for the buck." IQ-3 involves one-step "intensive" cooling in contrast to the multi-step cooling rates of the IQ-1 and IQ-2 processes. When the IQ-3 process is applied, part surface cooling is so fast that both the film boiling and nucleate boiling are completely avoided and the basic heat transfer mode on the part surface is simply convection. Therefore "direct convection cooling" is the first key element to the IQ-3 process.

In the IQ-3 method, intensive cooling is continuous and uniform over the entire part surface until compressive stresses on the part surface reach their maximum value and optimal depth depending on part geometry. These maximized compressive surface stresses will be diminished if the core of the part is cooled further, e.g., to the quenchant temperature. Therefore, the second key element of the IQ-3 process is to interrupt intensive cooling at the proper time – when compressive surface stresses are at their maximum value and to the optimum depth.

In practice there are three major issues to implementation of the IQ-3 quenching method. The first one is that it is not always possible to provide a high-velocity water flow *uniformly* around the *entire* part surface area. This is especially difficult to do for a part with complex geometry. The second limitation relates to quenching of relatively thin parts with the thickness of less than about ¼". With such thin parts it is very difficult to provide a proper temperature gradient within the part to get a 100% martensitic structure in the part surface layer, and, at the same time have an austenitic core that will convert to a hardened intermediate structure in the part core. For thin parts, the required high water flow velocity and the short time to "interruption" become in many cases impractical. Finally, IQ-3 method is not as adaptable to batch quenching of steel parts since it is practically impossible to provide high water flow velocity and uniformity throughout the entire batch. To quench intensively parts of complex shape, thin parts or parts in batches, the above IQ-2 quenching technique should be used. However, parts of thick cross-sections (more than ¾”) and parts of relatively simple geometry are ideal candidates for IQ-3 quenching.

1.2.4 What Is The Difference Between Induction Case Hardening and IntensiQuench^{SM} Processes? This is a very commonly posed question. Like IntensiQuench^{SM}, induction case hardening (ICH) provides the part with residual compressive surface stresses and with a wear resistant, martensitic surface. However, unlike intensive quenching processes, the ICH process only strengthens the part surface layer. The part core does not experience any phase transformations. If “core conditioning” is required, the part must be through heated, quenched and tempered prior to conducting ICH. This is in contrast to the IntensiQuench^{SM} methods that provide high compressive surface stresses and *at the same time* strengthen the core.

Secondly, the ICH process creates a hardness profile and residual stress profile that are much steeper than those after intensive quenching. And finally, intensive quenching is interrupted when residual surface compressive stresses are at their maximum value providing the part with an optimum hardened depth. The smoother hardness profile, the high residual stresses and the optimum depth of hardness after IQ processes result in better part performance characteristics – all in one process.

2. Intensive Quenching Process Computer Model

With IQ Technologies’ proprietary computer models an IntensiQuench^{SM} process can be adapted to almost any steel part. The process begins by analyzing the thermal and stress profiles within the part during quenching using a finite element approach. A computer model was developed to conduct this analysis (**Reference 2**). This model includes a non-linear transient heat conduction equation and a set of equations describing the thermoplastic-plastic flow with kinematic strengthening on the parts’ surface.

An iterative technique is used to solve the system of equations. At each time and space step, the calculation results are compared with the thermokinetic diagram of the supercooled austenite transformation, and new thermophysical and mechanical characteristics for the next step are chosen. This analysis seeks the point along the cooling curve where compressive surface stresses are maximized. The calculation results are:

- Temperature field
- Material phase composition
- Stress distribution
- Distortion distribution
- Duration of each cooling step for IQ-3 and IQ-2 quenching methods –The “Cooling Recipe”

Data from numerous laboratory and field experiments has been used in the validation of this model. A similar software package, the DANTE model, was developed by a collaborative research program managed by the National Center for Manufacturing Science (**Reference 7).** However, in contrast to the computer model developed by Dr. Kobasko, this software does not calculate the heat transfer boundary conditions on the part surface during the various stages of the quench. An accurate evaluation of the heat transfer on the part surface is a key element in this type of calculation leading to greater accuracy in predicting real world results.

A simplified computer program was also developed to calculate cooling recipes for IQ-3 and IQ-2 quenching techniques. This computer program uses generalized correlations between the cooling time and part characteristics (geometry, dimensions, type of steel, etc.). These correlations were obtained by using an extended experimental and computational database for steel parts of various geometries.

3. IQ Equipment

Currently there are two general types of IQ equipment. The first type of IQ systems is for the implementation of the IQ-3 quenching technique for a single (part-by-part) quenching method. The second type of the IQ systems is designed for IQ-2 batch quenching of multiple steel parts or for single-part quenching of parts with very complex geometry.

3.1. IQ-2 Quenching Equipment. IQ-2 quenching systems are similar to conventional oil quench tank designs used in batch and continuous operations. The differences are the following. As mentioned in Section 1.1.2, the IQ-2 quenching technique uses a low concentration (less than 10%) mineral salt/water solution, instead of oil, or polymer/water. Secondly, IQ-2 systems must have a significantly higher quench agitation rate. For example, a full-scale 6,000-gallon IQ-2 quenching system, installed at Summit Heat Treating Co. (Akron, Ohio), is equipped with four 18” diameter props rotated by four 10 horsepower motors. A similar oil-quench tank in an integral quench batch type furnace would be equipped with only two props rotating by two 5 hp motors. In the case of batch operations, IQ-2 quenching systems should be equipped with a very fast elevator mechanism since the duration of different IQ-2 process cooling steps is usually calculated in seconds. Moving from “intensive water quenching” to “still air quenching” of the load should be completed within 2 to 3 seconds. And finally, the IQ-2 quenching system should be automated to control the duration of each the three steps of the IQ-2 cooling recipe - “intensive” to form properly the “shell,” then to “air” cooling, then back to “intensive” cooling. (See Section 1.1.2).

Existing oil tanks in integral quench furnaces or continuous furnaces can be modified relatively easily to accommodate the IQ-2 quenching method. When retrofitting an existing integral quench atmosphere furnace (for example, an All-Case™ Surface Combustion furnace), extra care should be taken to seal the door between the furnace and the cooling chamber to maintain the integrity of the furnace atmosphere from contamination by water vapors. (Note that AFS-Holcroft integral polymer/water or salt quench furnaces use a three-chamber approach to maintain atmosphere integrity. They use an intermediate, purge chamber, between the furnace and the quench tank, equipped with a handling mechanism.) In continuous furnace line quench tanks, it is usually necessary to re-design the parts conveyer by fitting it with a variable speed drive to vary the parts’ cooling “time-in” and “time-out” of the IQ-2 quench media.

3.2. IQ-3 Quenching Equipment. To implement the IQ-3 quenching technique it is necessary to provide uniform and intensive heat extraction from the part surface, to create a “shell” with maximum compressive stresses to an optimum depth. Once the shell is properly formed the intensive quench is interrupted and the part cools in the air with the core cooling by uniform conduction through the cold shell. IQ-3 can be accomplished in two ways. For parts with relatively simple geometry (for example, cylindrical parts, flat parts, etc.), a high velocity water flow along the part surfaces can provide the required “intensive” cooling (heat transfer coefficients). For parts of more complicated shapes (for examples, shafts with flanges that can block the water stream flowing along the part axis), a water jet impingement approach is a very effective way of uniform, intensive cooling. In both these cases, a pump or pumps provide the necessary “intensive” water flow velocity and uniformity. A typical IQ-3 system includes a water tank, pump(s), valves, piping, water flow, temperature and pressure control devices, automated part handling system, and a water-chilling system.

Note that all IntensiQuench℠ quenching systems are compatible with any kind of through heating equipment: gas-fired atmosphere, induction, bath salt, vacuum, etc. As with conventional through hardening and quenching, all that is necessary is that each part be heated to the austenitic temperature and presented to the quench system in a timely fashion.

4. IQ Process Experimental Validation

The IntensiQuench^{SM} process has been validated by hundreds of laboratory and field experiments. A few examples are summarized below, including examples from recent demonstration projects in the U.S. The part makers conducted all metallurgical analysis and fatigue testing. Some metallurgical tests were performed by Case Western Reserve University of Cleveland, Ohio. The details of the experimental data summarized below are available upon request from IQ Technologies Inc.

4.1 Hardenability Improvement

Table 1. As –quenched Hardness for Different Materials (Parts were quenched through)

Quench	Hardness, HRC		
	40Cr* (AISI 4140) M10 Bolt	4037 M18 Bolt	5160H Bar ∅1.4”
Oil	42.7	51-47	60.4
Intensive	54.8	58-60	63.4

*) **Reference 8**

Table 2. As-tempered Core Hardness Improvement

Part	Core Hardness*, HRC	
	Oil	IQ
86B30 steel 25×25 mm sprocket tooth**	36	50
52100 steel 19 mm wall thickness bearing ring**	56	61
4140 steel ∅45×264 mm kingpin**	30	48
1045 steel ∅25.4×254 mm keyway shaft***	31	50
4137 steel 110x116 mm forged shoe	42	47
4130 steel 129x137 mm forged wedge	29	38

*) Parts were tempered at the same temperature after intensive quenching and oil quenching.
**) Reference 9
***) Reference 19

Table 6. 86B30 Five-Tooth Sprocket Hardness and Hardened Depth (Reference 10)

Quench	Hardness, HRC		Hardened Depth, inch
	Surface	Core	
Intensive	52.0	50.2	Hardened through
Oil	50.0	36.5	1/8”

The enhanced hardenability provided by the intensive quenching process means part designers can reduce alloy content and lower finished part costs.

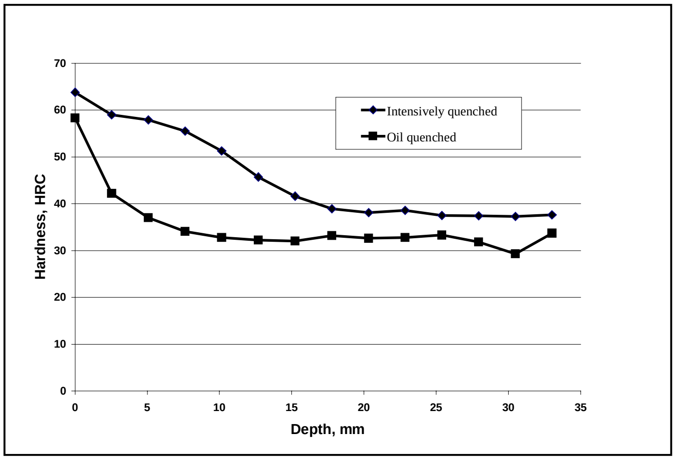


Figure 7 As-Quenched Hardness Distribution for ∅73 mm 1547 Steel Cylinder (Reference 9)

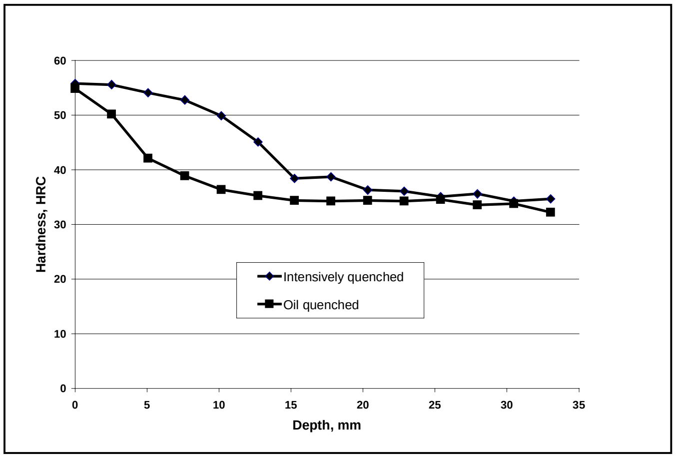


Figure 8 Tempered Hardness Distribution for ∅73 mm 1547 Steel Cylinder (Reference 9)

The hardness in the intensively quenched sample has reached a depth of hardness that is more than 7 times greater than that of the oil quenched sample, measured at the 50 HRC level.

Table 7. Microstructure at Various Locations of ∅1.4” 5160 Torsion Bar (Reference 9)

Part	Quenching	Bainite Content, %				Grain Size
		Surface	Near Surface	½ Radius	Core	
∅36 mm 5160 Steel Torsion Bar*	Intensive	0	0	2.0	2.5	-
∅36 mm 5160 Steel Torsion Bar	Oil	3.0	5.0	12.0	29.0	-
∅21 mm Wire 9259 Steel Spring	Intensive	0	-	-	2.0-5.0	ASTM 9
∅21 mm Wire 9259 Steel Spring	Oil	5.0-10.0	-	-	15.0-20.0	ASTM 8

Note: *) Reference 9
**) Reference 19

IntensiQuench^{SM} process provides better near surface and core microstructure, and finer grain size.

4.2 Mechanical Property Improvement.

Table 8 Mechanical Properties at the Core of Conventional and Intensively Quenched Steels (Samples were taken from the core of ∅50 mm specimens, References 11 and 18)

Soviet Steel (AISI Steel)	Quenching	Tensile Strength, MPa	Yield Strength, MPa	Impact Strength, J/sm^2	Hardness, HRB
40X (5140)	In oil	780	575	113	217
	Intensive	860	695	168	269
35XM (4130)	In oil	960	775	54	285
	Intensive	970	820	150	285
25X1M (4118)	In oil	755	630	70	229
	Intensive	920	820	170	285

While intensive quenching improved all the mechanical properties, *the impact strength increased by 2 to 3 times.*

Table 9 Mechanical Properties Improvement for Different Parts (Reference 9, 16 and 17)

Part	Property	Oil Quench	Intensive Quench
1340 steel M22×123mm bolt	Tensile strength, MPa	1093	1176
S5 steel ∅38×56 mm punch	Impact strength, N×m	6.8	12.2
4140 steel hand tool socket	Torque to failure, N×m	168.6	223.3
4140 steel ∅45 mm king pin	Ultimate strength, kN	313.6	414.8

The IntensiQuench^{SM} process provides parts with better mechanical properties due to enhanced hardenability and finer martensite structure.

4.3 Compressive Residual Surface Stresses.

Table 10. Experimental Residual Surface Compressive Stresses for Different Steel Parts

Part	Residual Surface Compressive Stresses, MPa	References
52100 Ring ∅8.5”	-136	9
52100 Roller ∅3”	-348	-
4140 Kingpin ∅1.8”	-563	9
S5 Punch ∅1.5”	-750	9
5160H Torsion Bar Sample ∅1.4”	-311	9
1045 Cylinder ∅1.5”	-430	12
1547 Cylinder ∅2.87”	-626	9
1547 Cylinder ∅2”	-515	9

The IntensiQuench^{SM} process provides the steel parts with significant surface compressive stresses resulting in longer part service life. IQ also can reduce or eliminate the need for carburization to achieve residual compressive surface stresses.

4.4 Increase Part Service Life.

Table 11. Parts' Lifetime Improvement

Steel Part	Type of Steel	Lifetime Improvement*, %	Ref.
Truck half-axles	4340 (oil quench) 1045 (intensive quench)	760	11
Shafts	81B40 (oil quench) 1045 (intensive quench)	800	13
Punches	Shock-resisting S5	100	-
Punches	High-speed steel (equivalent to M2)	50-100	14
Dies	52100	50-100	15
Forklift forks	15B35H	20	-
Automotive coil springs	9259	30	-
Automotive leaf springs	5160	85	-
Pulverizer coil springs	8660	300	-

Note:*) Based on actual cycle test data.

Intensive quenching provides significant part service life improvement due to improved mechanical properties and the presence of compressive surface stresses. The service life of the intensively quenched parts made of plain carbon steel is *7.6-8.0 times longer* that of the same configuration parts made of alloy steel and quenched in oil.

Table 12. Thermal Fatigue Improvement of 2"× 2"×5" H-13, Aluminum Die Casting Test Block (Reference 9)

Number Thermal of Cycles	Maximum Crack Length, $\times 100 \mu m$		Total crack Area, $\times 10^6 \mu m^2$	
	Oil	Intensive	Oil	Intensive
5,000	1.0	0	0	0
10,000	4.4	5.4	13.8	22.4
15,000	17.1	12.4	163.8	94.4

IntensiQuench^{SM} process gives H-13 die-casting steel (traditionally an "air-hardening" alloy) greater resistance to heat checking (as measured by shorter average heat cycle crack length and less total crack area) resulting in longer die service life.

4.5 Shortening/Elimination of Carburization Cycle with the Same or Better Hardness Profile.

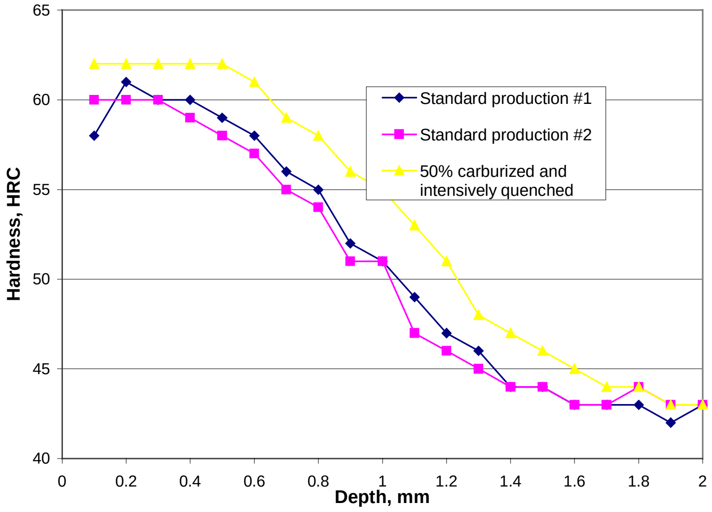


Figure 9 Hardness Distribution Throughout 8617 Bearing Cage with Wall Thickness of 4 mm and Case Depth of 1.2-1.5 mm

Bearing cages that were carburized for *only 50% of a standard carburization depth* and intensively quenched have a *better hardness profile* than the same bearing cages that were carburized to 100% of the specification depth and quenched in oil per the standard production practices.

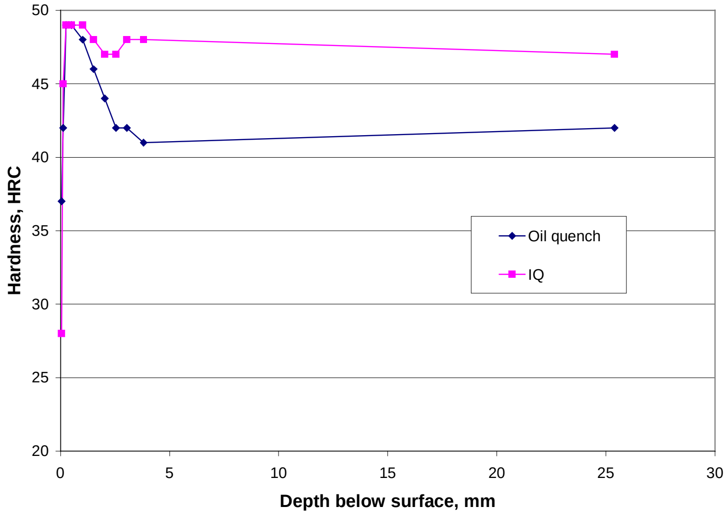


Figure 10 Hardness Distribution Throughout 4137 Forged "Shoe" Cross Section of 110x116 mm and Case Depth of 1.5-2.0 mm

After intensive quenching, the hardness distribution in the "shoe" (below the carburized case) shows that there is no need to carburize this part – IntensiQuench^{SM} without carburization gives sufficient hardness depth with the same alloy.

4.6 Reduction of Part Distortion through IntensiQuench^{SM}

Table 13. Measurement of Shaft Distortion (1045 Material, ∅25.4 mm Shaft with 6.4 mm X 6.4 mm Keyway)

Single Oil Quenching	Batch Oil Quenching	Intensive Quenching
0.20-0.36 mm	**0.25-0.51 mm**	**0.08-0.12 mm**

Note: *) Height of the shaft bow (Figure 11)

Intensive quenching causes much less shaft distortion compared to both single-part oil quench and batch oil quench.

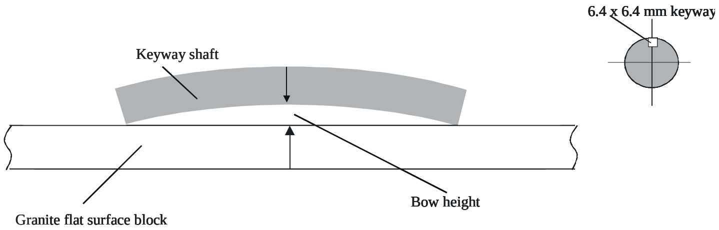


Figure 11 Keyway Shaft Distortion

5. Summary of IQ Process Benefits

In summary, IntensiQuench^{SM} processes have been shown to increase part hardness and strength, ***while at the same time providing less part distortion*** on typical products made of various steel types. IQ Technologies, Inc. offers computer process modeling and proven design tools for implementing intensive water quenching technology for a wide variety of steel alloys with varied part geometry. Manufacturers of steel parts can **improve their product quality *and* reduce their costs** utilizing IQ Technologies' proprietary software and processes. Some of the proven advantages of intensive quenching include:

- ⇒ Elimination of cracking
- ⇒ Minimization of distortion and associated costs
- ⇒ High residual compressive surface stresses for greater part durability
- ⇒ Reduction or elimination of carburization cycles
- ⇒ Improved mechanical properties (yield and ultimate strength, wear resistance, depth of hardness, etc.)
- ⇒ Reduction of part size/weight with comparable physical properties
- ⇒ Longer part life with no cost penalty
- ⇒ Usage of lower alloy steels while maintaining physical properties (enhanced value engineering)

- ⇒ Replacement of hazardous quench oil with environmentally friendly water or salt/water solutions
- ⇒ Better integration of the heat-treating process into the production process flow.

For detailed information concerning application of the IntensiQuench^{SM} process to your heat-treating operations, please contact us at:

IQ Technologies, Inc.
655 S. Broadway, Akron, Ohio 44311
Phone: (330) 253-3900, Fax: (330) 253-3820

Or visit our web site: **www.IntensiveQuench.com**

We will be glad to provide you with specific information on how IQ Technologies can significantly improve your part quality and strength, while lowering your total processing costs.

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