Intensive Quenching Theory and Application for Imparting High Residual Surface Compressive Stresses in Pressure Vessel Components

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An alternative method for the hardening of steel parts has been developed as a means of providing steel products with superior mechanical properties through development of high residual compressive stresses on the part surface, and involves the application of intensive quenching during heat treatment. This processing method, termed "Intensive Quenching," imparts high residual compressive stresses on the steel surface, thus allowing for the use of lower alloy steels, reduction or elimination of the need for carburization and shot peening, and providing for more cost-effective heat treating. Intensive quenching also provides additional environmental benefits, as the process uses plain water as the quenching media in contrast to traditional heat treatment practices which typically employ hazardous and environmentally unfriendly quenching oil. This paper presents an overview of the theory and application of intensive quenching, as well as provides experimental and computational data obtained for a variety of steel products. Also presented will be results of computer simulations of temperature, structural and stress/strain conditions for a typical pressure vessel during intensive quenching. [DOI: 10.1115/1.1556858]

Background and 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 in 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 a low cooling rate in martensite 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 [1,2]. A large number of field experiments on a variety of steel parts validated both the theory and the computer simulation [3,4].

Figure 1 shows experimental data obtained for a cylindrical specimen made of a low alloy steel with a diameter of 6 mm (about 0.25 in.). 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. This high cooling rate regime is termed "intensive quenching." The curve also shows that once quenching is in the "intensive zone" or above, the benefits of using this 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.

Mechanism. Imagine a steel part with a varying thickness (Fig. 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 section (Fig. 2(*a*)). 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 transforms to 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" (Fig. 2(*b*)). Dr. Kobasko's research showed that this uniform, hardened shell creates high compressive stresses resulting in lower distortion and lower probability of cracking.

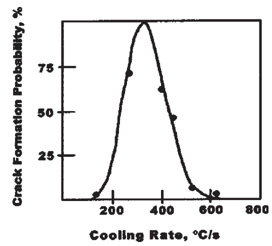

Fig. 1 Effect of cooling rate on probability of cracking

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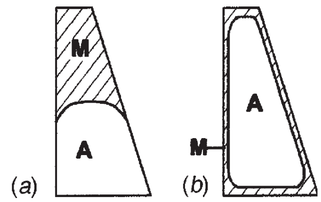

Fig. 2 Martensite formation during quenching—(*a*) Conventional, (*b*) Intensive

Compressive Stress Formation. To simplify a mechanism of the stress formation in the part, 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'' (Fig. 3). When the whole steel part is austenitized (heated and held above Ac_3 temperature) before quenching there is no tension in the ''springs'' and there are no stresses between the ''segments'' ($\sigma=0$); see Fig. 3(*a*). 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 during cooling, the ''springs'' expand simulating the development of tangential (hoop) *tensile* thermal stresses; see Fig. 3(*b*).

When the surface layer reaches the martensite formation start temperature, Ms, the austenite in the surface ''segments'' transforms into martensite; see Fig. 3(*c*). The martensite specific volume is greater than that of austenite. 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 (Fig. 3(*d*)). 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 Fig. 3(*d*)). This is because the hot austenite is in a ''plastic'' state; and 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 Fig. 3(*e*)). 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 in intensive quenching 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 and pearlite; (see Fig. 3(*f*)). Since this mixed ''core'' structure has less specific volume than a ''pure'' martensite core (as discussed, in the foregoing), the interrupted quench results in a higher level of surface residual compressive stresses when compared to the through-hardened version (see Fig. 3(*e*)). 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.'' As such, intensive quenching is robust and practical for production environments.

It is important to note that the ability of intensive quenching to create 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. This is because in conventional quenching the part cools several times slower than in intensive quenching, and the temperature gradient throughout the part is small. Therefore, in standard quenching, the part core temperature is just above the M_s temperature when martensite starts forming in the part surface layer. In contrast, in intensive quenching the part core is very hot at the same moment of time (Fig. 3(*c*)). The pre-phase transformation shrinkage of the core in this case is negligible compared to intensive quenching (see Fig. 3(*d*)) and it does not offset the subsequent core expansion. This is the metallurgical ''key'' to the process. In non-intensive quenching, part core expansion is actually greater than the pre-phase transformation thermal shrinkage. Therefore, after conventional quenching, the swelled core pushes apart the surface ''segments'' creating tensile stresses on the part surface (the

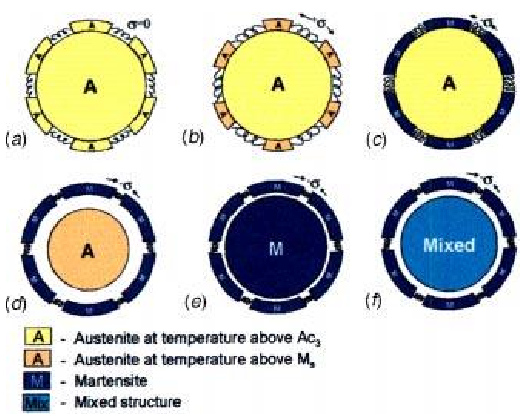

Fig. 3 Surface stress conditions during intensive quenching

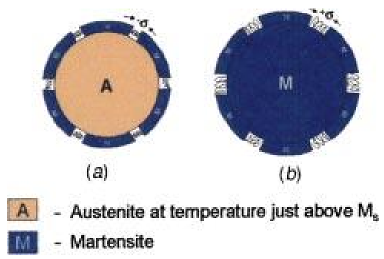

Fig. 4 Surface stress condition during conventional quench

"springs" between the "segments" expand, as shown schematically in Fig. 4. This is why many conventionally quenched parts are very "unstable" and may crack if not tempered soon after quenching.

Curve I on Fig. 5 provides an additional illustration of the dynamics of the surface stress conditions during intensive quenching over time with a "mixed core," while Curve II on the same figure illustrates the dynamics of the "surface" stress conditions during intensive quenching over time with a "martensitic core" structure. In both cases the initially created surface compressive stresses are of such magnitude so as to be able to remain in residual compression even after subsequent transformation and expansion of the core. In contrast, the lower level of surface compression created during the initial quenching stage using a standard immersion practice is insufficient to withstand the subsequent core transformation, often resulting in a net neutral or tensile residual surface stress (Curve III on Fig. 5).

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 (Fig. 6). Once the "shell" is cool and is in deep 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.

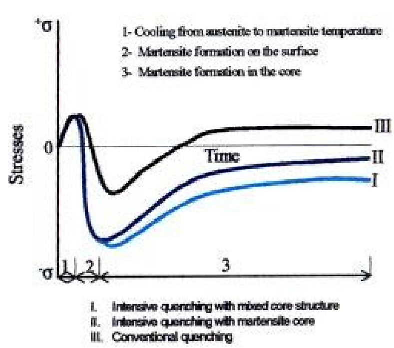

Fig. 5 Surface stress versus time

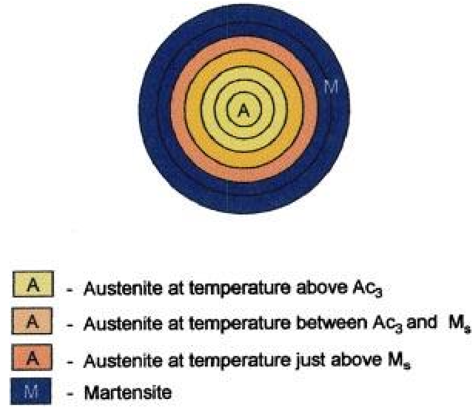

Fig. 6 Part structure concentric layers

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 [5,6].

Optimum Hardened Depth. Analysis conducted by Dr. Kobasko 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 in consideration of 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 the 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. Computer modeling provides a high level of accuracy in predicting and determining this optimum depth.

The intensive quenching method will provide an optimum combination of high residual compressive surface stress; high strength and wear-resistance due to high surface hardness; a quenched layer of optimum depth; and a relatively soft but properly strengthened core [4]. This combination is ideal for applications requiring high strength 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). The process has been used successfully on solid parts with section sizes up to 40 in.

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

IQ Process Computer Model

Development of an intensive quenching process begins by analyzing the thermal and stress profiles within the part during quenching using a finite element approach. Dr. Kobasko and his colleagues developed a two-dimensional computer model to conduct these analyses [5]. This model includes a non-linear, transient heat conduction equation and a set of equations for the theory of thermoplastic flow with kinematic strengthening under the appropriate boundary conditions on the part's surface. Numerous laboratory and field experiments have been used in the validation of this computer model.

A similar but three-dimensional software package, DANTE,[1] was developed in the US on the collaborative research program managed by the National Center for Manufacturing Science [10]. However, in contrast to the computer model described in [5], the DANTE software does not calculate heat transfer boundary conditions on the part surface; rather, DANTE involves the application of heat transfer coefficients or fluxes at part surfaces. An accurate characterization of these conditions is a key element to the accuracy of such calculations. The analysis results that are presented in this paper are based on the DANTE software package, with boundary conditions determined using Dr. Kobasko's computer model.

For an evaluation of the potential for application of the intensive quenching method to the heat treatment of pressure vessels, three possible intensive quenching methods were simulated and compared with predicted simulation using standard water quenching techniques. The pressure vessel under evaluation was chosen as a generic open end cylinder (blind end vessel) with OD = 457.2 mm (18.0 in.), ID = 228.6 mm (9.0 in.), and length = 1270 mm (50.0 in.) made of 4340 steel. The normal manufacturing route for this type of pressure vessel involves forging of the vessel shell, preliminary machining, heat treatment, and possible final machining. The cylinder is typically heat treated by horizontal immersion, with agitation applied to the internal cavity to avoid excessive buildup of vapor. Application of the intensive quenching process is designed specifically to impart compressive stresses onto the affected surface regions of the heat treated pressure vessel.

To model both the standard and intensive quenching processes, a two-dimensional mesh was prepared for an axisymmetric section (one-half) of the 1270 mm (50 in.) long "blind end" pressure vessel previously described. The 2D mesh is shown in Fig. 7, and contained 3056 nodes with 2850 quadrilateral elements. Both models assumed a uniform starting temperature of 900°C and a completely austenitic microstructure that was stress free. Quenching was simulated through the application of surface heat transfer coefficients that were supplied by IQ Technologies Inc. for both the standard immersion and intensive quenching processes [17,18]. The DANTE material model was used for the quench hardening simulations, using the ABAQUS[2] finite element solver. In this application, intensive quenching used highly agitated water as the quench medium. An extremely high level of water flow is necessary to eliminate not just film boiling but also nucleate boiling during quenching so that intimate contact between the pressure vessel and water is maintained. Based on experiments conducted by IQ Technologies Inc., surface heat transfer coefficients of 20 to 40 $kW/(m^2 {*} C)$ are achieved during intensive quenching. For comparison, peak heat transfer during water quenching is on the order of 5 $kW/(m^2 {*} C)$ and the average is less than 1 $kW/(m^2 {*} C)$.

Two simulated heat treatments for the pressure vessel were evaluated; one using the current "standard" immersion water quench, and the other three using a customized intensive quenching process designed to provide a relatively equal heat flux density between inside and outside surfaces. Processing data for the simulation of each heat treatment is presented in Table 1. Resulting microstructure and stress states were then examined in each simulated case.

[1]DANTE is a registered trademark of Deformation Control Technology, Inc., Cleveland, OH.

[2]ABAQUS is a registered trademark of HKS, Inc., Pawtucket, RI.

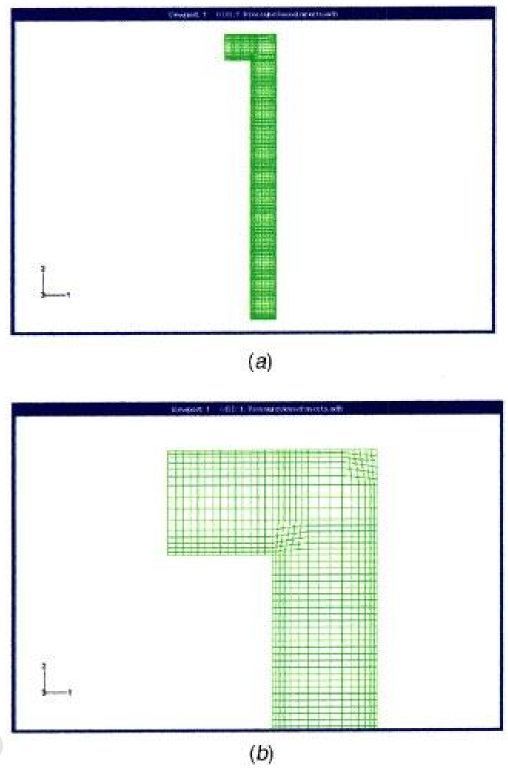

Fig. 7 Finite element model mesh developed for pressure vessel heat treatment evaluation—(*a*) overview of axisymmetric mesh (*b*) close-up of closed end illustrating surface mesh refinement

Standard Quench—Microstructure and Stresses. Simulation of the standard horizontal immersion quenching of the pressure vessel produced the time-temperature history shown in Fig. 8. Note the maximum thermal gradient from surface to center is about 330°C at about 2 min into the quench.

Figure 9 shows a contour map of the resulting hoop stress through the vessel cross section upon completion of the immersion quench (stress in MPa). Note that the difference between the interior and exterior surface areas contributes to a slight difference between the inner and outer surface temperature profiles, which is in turn manifested in a difference between resulting surface hoop stresses—with the interior displaying lower residual surface compression than the outside.

Table 1 Process data used for simulations

	Standard	IQ Case 1
Aust. temp	900°C	900°C
Quenchant ambient	30°C	30°C
Orientation	Horizontal	Horizontal
Exterior heat transfer	700 W/m^2 K	700 W/m^2 K
Interior heat transfer	700 W/m^2 K	20,000 W/m^2 K
Quench time	40 min	32 min

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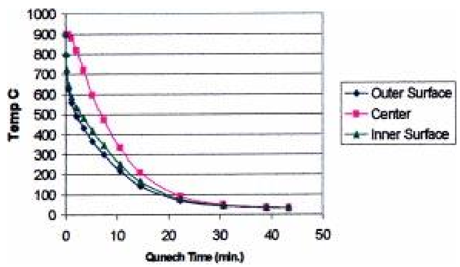

Fig. 8 Time-temperature history for oil quenched pressure vessel section

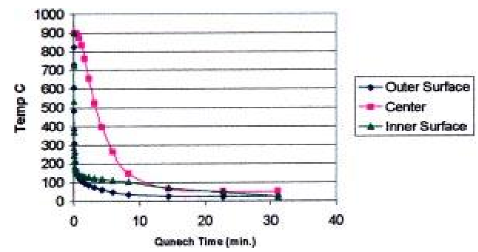

Fig. 11 Time-temperature history for intensively quenched pressure vessel section, illustrating extreme thermal gradient

Figure 10 shows a time history of both residual hoop stress and transformation behavior for both the vessel surfaces and center. Note that both the inner and outer surfaces are predicted to be under residual compressive stresses, and that the time at which these stresses reach their maximum is well after completion of transformation.

As the history plot in Fig. 10 shows, the majority of the compressive surface stresses are generated after transformation of the core, and are developed primarily through thermal shrinkage of the core. This is standard behavior in large or thick-section parts. The final microstructure is predicted to be mostly ferrite-pearlite and bainite with no martensite.

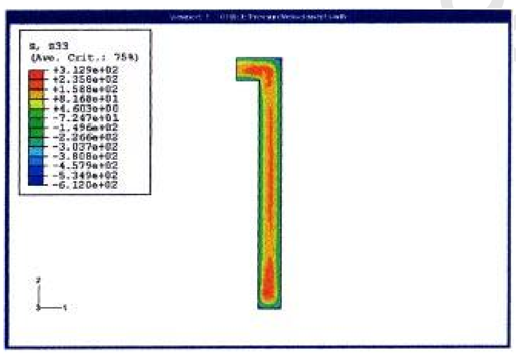

Fig. 9 Profile of residual hoop stress in pressure vessel cross section after oil quench (units=MPa)

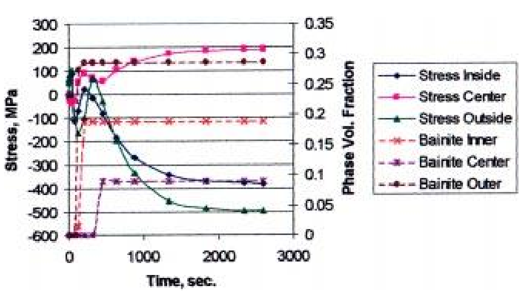

Fig. 10 Time history plot for hoop stress and phase volume fraction for surface and core areas within the pressure vessel during oil quenching

Intensive Quench—Microstructure and Stresses. In the Case No. 1 intensive quenching scenario, the process designed and proposed for this application involved application of a highly agitated saltwater solution to provide continuous convective cooling of the outside surface, calculated as 7 kW/m^2K. On the interior of the pressure vessel, this same solution provides a higher average heat transfer (on the order of 20 kW/m^2K) due to nucleate boiling. There are three principal regimes of boiling with respect to surface heat transfer behavior: film boiling, nucleate boiling, and free convection [19]. During nucleate boiling, which typically occurs within about a 30°C temperature range, bubbles form at nucleation sites and continually separate from the quenched surface. This separation induces considerable fluid mixing and substantially increases both the surface heat flux and consequent heat transfer coefficient. Directed quenchant agitation, as well as certain chemical additives, are employed in the intensive quenching process to maximize this effect. Specifically, this IQ process was designed to provide a relatively equal heat flux density between inside and outside surfaces. As shown in Fig. 11, the resulting surface to center thermal gradient is now substantially higher; on the order of 700°C for the interior to center, and 800°C for the outside surface to the center.

The time history for residual hoop stress and transformation behavior for this quenching scenario is shown in Fig. 12. In this case note that the surface phase transformation is martensitic, and that this transformation is completed well before the bainite transformation in the center even begins. The core remains in a fairly neutral stress state until it transforms to bainite (30%) and ferrite-pearlite (70%), at which time it briefly expands generating tensile stresses in the center and very slightly reducing the compressive stresses at the surface. However, the bulk of the surface compressive stresses remain intact due to the inherent strength of the martensite phase, even during subsequent cooling with the associated thermal shrinkage.

Figure 13 shows the final predicted metallurgical phase fractions present in the cross section at the end of quench, with the

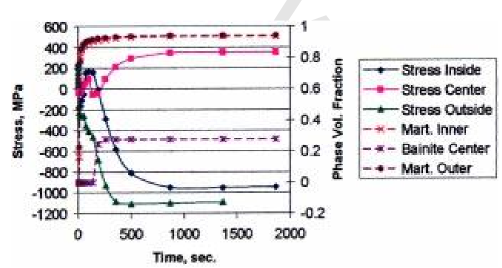

Fig. 12 Time history plot for stress and phase volume fraction for surface and core areas within the pressure vessel during intensive quenching

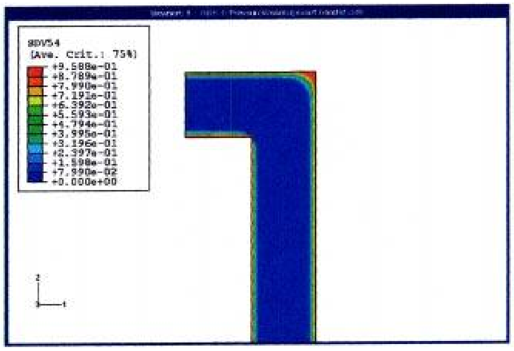

Fig. 13 Contour plot of martensite phase volume fraction in the pressure vessel section at the end of intensive quenching

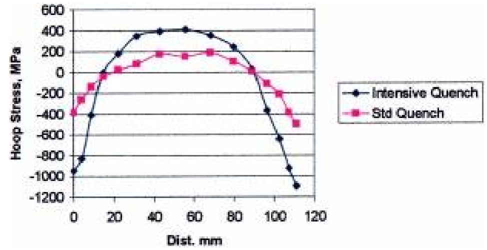

Fig. 15 Comparative stress profiles through the vessel section for both quench scenarios

corresponding final hoop stress profile shown in Fig. 14. Again, the primary feature is the predicted predominant martensitic surface layer and much higher level of beneficial surface compressive which extend deeper into the cross section.

Comparison of Quench Simulation Results and Implications.. A more detailed comparison of the standard and intensive quenching simulation results as applied to heavy section steel components reveals several important differences, benefits, and limitations.

First, in heavier section components the thermal gradients generated in both quenching techniques are more localized at the component surface, though in intensive quenching the magnitude of 700 to 800°C is substantially higher than the magnitude of about 100°C for oil quenching. The ability to complete the surface martensitic transformation prior to the initiation of the core bainite-ferrite-pearlite formations in intensive quenching provides important resistance to the later damping of the resulting surface compressive stresses due to subsequent transformations in the core.

The general propensity for the generation and retention of surface compressive stresses is greater in larger, thicker steel sections than in thinner ones. This is because in general, the thermal gradients created in the larger sections are insufficient to create martensite in the core to a degree which would counteract the surface compression created by the formation of martensite at the surface. Thus the use of the intensive quenching technique generally has a greater benefit in thinner than in thick sections, though it is still beneficial in thick sections as well. In these thicker sections, which often retain some degree of surface compression after standard quenching, intensive quenching will impart even greater surface compressive stresses, as indicated in the comparative plot shown in Fig. 15.

The graph in Fig. 15 indicates an almost ×2 increase in surface compressive stress for the intensively quenched section as compared to the standard quench. However, due to the limiting effect of thermal conductivity, the presence of compressive stress in general (for both the intensive and standard quenching) is limited to a depth of about 20 mm.

An overall improvement in surface and through-hardness results is also predicted by employing intensive quenching on the large section pressure vessel. The plot presented in Fig. 16 illustrates the predicted hardness profiles for both the standard and intensively quenched pressure vessel sections. The benefit of intensive quenching is the achievement of martensite on the surface and a higher bainite content in the core as opposed to bainite-ferrite-pearlite throughout the oil quenched cross section.

The general implications and potential benefits of employing the intensive quenching technique to pressure vessel sections involve potential enhancements in service performance. It is well known that compressive hoop stresses are beneficial in applications where fatigue life of a component is important, as they are in the case of a pressure vessel. The enhanced residual surface compressive stresses produced by the intensive quenching process would provide improved resistance to fatigue during pressurization and depressurization cycles and enhance vessel life. In addition, though not evaluated directly in this study, the application of intensive quenching has also been shown in several component trials to markedly reduce part distortion, as the rapidly developed and very high strength martensitic shell acts to quickly ''lock-in'' the part shape [20].

The intensive quenching process has been evaluated in the manufacturing setting for a variety of alloy steel applications requiring enhanced fatigue performance [21,22]. As presented in

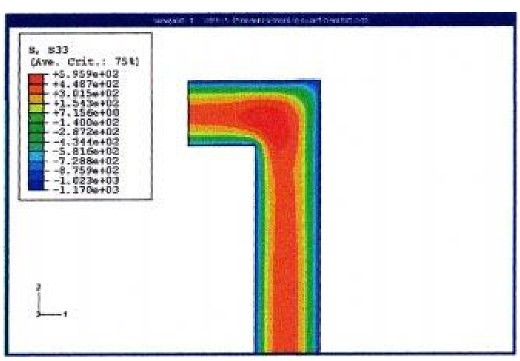

Fig. 14 Profile of residual hoop stress in pressure vessel cross section after intensive quench (units=MPa)

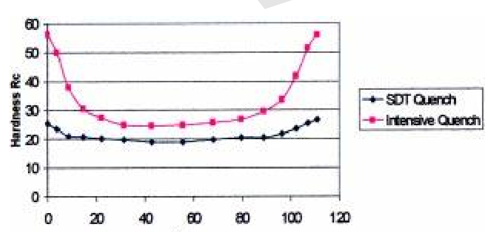

Fig. 16 Comparative hardness profiles (predicted) for both quench scenarios

Table 2 Summary of life cycle improvement evaluation for intensive quenching

Application	Material	Lifecycle improvement
Truck half-axle	4340 oil quench versus 1045 intensive quench	760%
Shaft	81B40 oil quench versus 1045 intensive quench	800%
Concrete breaker point	4340 oil quench versus 1078 intensive quench	From 1 h (oil quench) to no failure (intensive quench)
Punch	High-speed steel	50–100%
Die	AISI 52100	50–100%

summary outlined in Table 2, intensive quenching has been shown to provide significant part lifecycle improvement due to both improved mechanical properties and the presence of the beneficial surface compressive stresses. The lifetime of the intensively quenched parts made of plain carbon steel proved to be 50–800% longer than parts made of alloy steel and quenched in oil. All evaluations were performed independently of heat treatment developer.

With respect to specific application of the intensive quenching technique to pressure vessel applications, further evaluation involving physical testing of hollow cylinder specimens is required. In this regard, an associated study is currently underway with the US Army, Watervliet Arsenal to specifically assess the benefits of intensive quenching over standard autofretage in the manufacture of cannon barrels. In the potential for providing improved fatigue life and minimal part distortion in heat treatment (leading to a reduced need for final machining), the intensive quenching technique displays promising potential for application in the production of pressure vessels.

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