Intensive Quenching Processes Basic Principles, Applications and Commercialization

Michael Aronov[1], Nikolai Kobasko[1], Joseph Powell[1], Bill Andreski[2], Bob O'Rourke[3]

[1]*IQ Technologies Inc, 336 Morgan Ave., Akron, Ohio, USA 44311, info@intensivequench.com*

[2]*MetConsult, 18566 Whitemarsh Lane, Strongsville, Ohio, USA 44149, metconsult@wowway.com.*

[3]*Dura-Bar, Subsidiary of Charter Manufacturing Co., 1800 West Lake Shore Drive, Woodstock, Illinois, USA 60098, borourke@dura-bar.com*

Abstract

The paper discusses basics of the intensive quenching (IQ) processes to achieve better part properties and performance characteristics, and outlines specifics of IQ equipment design and engineering. Two IQ techniques are considered: a batch IQ process conducted in IQ water tanks and a part-by-part processing IQ method conducted in high-velocity IQ units. The paper discusses major differences of heat transfer modes during these two IQ processes and the effect of extremely rapid cooling rate on the material microstructure and part mechanical properties. The paper presents the results of the case study on the application and commercialization of the IQ processes for steel mill rolls made of continuously cast ductile iron. Intensively quenched ductile iron rolls are used in several major steel mills in the USA. Data on the rolls microstructure, microhardness, residual surface stresses and service life after intensive quenching and conventional oil quenching are compared.

Keywords

Intensive quenching, steel mill rolls, heat transfer, microhardness, microstructure.

1 Basics of Intensive Quenching Process

An intensive quenching (IQ) process is an alternative method for hardening steel parts that uses highly agitated plain water instead of hazardous quench oils or polymers. In 1964, Dr. Kobasko proved experimentally that a correlation between the probability of part cracking during quenching and the cooling rate is actually represented by a "bell-shaped" curve rather than by a parabolic curve (Figure 1). The area at the end of the right side of the "bell-shaped" curve represents a so-called IQ zone: when quenching steel parts with extremely high cooling rates, the probability of part cracking tends to zero while parts are provided with superior mechanical properties and performance characteristics. This phenomenon takes place due to the following two factors: a) the development of very high *current* surface compressive stresses during intensive quenching that uniformly hold the part together as a die preventing

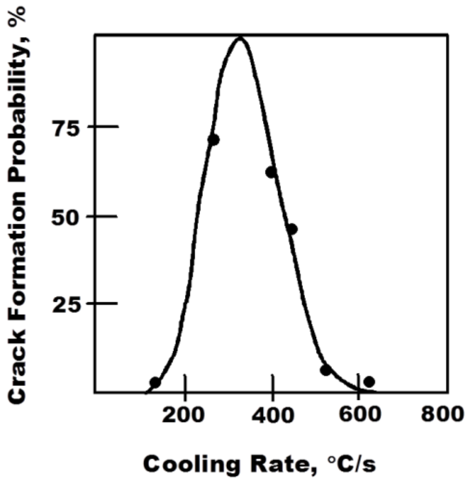


Figure 1: Experimental data obtained by Dr. Kobasko for Ø6mm bars made of alloy steel

cracking, and b) an interruption of intensive quenching at a time when these surface compressive stresses are at their maximum value resulting in the formation of high *residual* surface compressive stresses even after the completion of the phase transformation in the part core during followed cooling in the air.

1.1 Why does IQ process generate high surface compressive stresses?

Let's consider thermal and structural conditions for two identical parts one being quenched intensively in water and the other one being quenched in oil. An extremely high heat extraction rate during the IQ process creates a temperature gradient throughout the part thickness much greater than that during conventional oil quenching. At a time when martensite starts forming in the part surface layer, the core temperature of a part being quenched intensively is still close to its austenitizing temperature, while the temperature of the core of a part being quenched in oil is usually not much higher than the martensite start temperature. When martensite is forming in the part surface layer, surface compressive stresses develop in both parts due to the volumetric expansion of the material when transforming from austenite to martensite. These compressive stresses are increased by the thermal shrinkage of the part core: the thermally shrinking core pulls the martensitic surface layer inward inducing its compression. However, due to a much greater temperature gradient in the part being intensively quenched, the relative increase of the surface compressive stresses is much more pronounced for the intensively quenched part compared to the oil quenched part.

1.2 Why don't parts crack during intensive quenching?

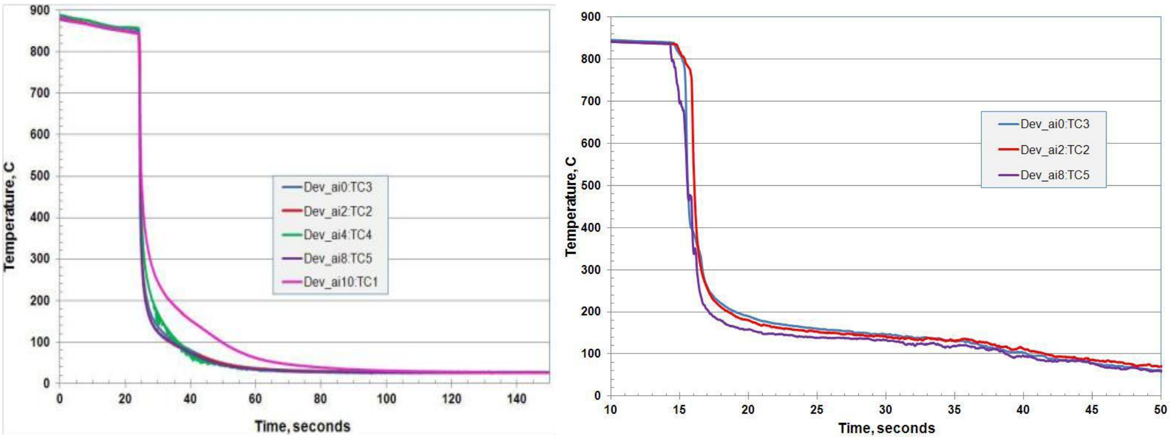
When quenching a part intensively, a key element for preventing part cracking is to provide surface compressive stresses not only during the quench but also after the IQ process is completed. This is achieved by interrupting of the IQ process at a time when surface compressive stresses are at their maximum value and continuing cooling the part in the air. Slowing down the cooling rate of the part prevents the formation of the martensitic structure in the part core resulting in a less cancellation of the surface compressive stresses. At the end of quenching, intensively quenched parts have always residual surface compressive stresses preventing parts from cracking. This is in contrast to oil quenched parts when residual surface stresses are usually neutral or tensile.

2 Specifics of Heat Transfer During Intensive Quenching

Two IQ techniques are currently used in heat treat practice: a batch IQ process conducted in IQ water tanks and part-by-part processing IQ method conducted in high-velocity IQ units. Major differences of heat transfer modes during these two IQ processes are discussed below.

2.1 Single-part quenching IQ process

When quenching parts one by one in high-velocity IQ units, the water is flowing along the part so fast that it doesn't have a chance to reach the boiling temperature. Neither film boiling nor nucleate boiling are present during the single-part quenching IQ process. A convection mode of heat transfer takes place practically from the very beginning of the quench. The heat transfer coefficients during this type of the IQ process are extremely high. The part surface temperature drops below the water boiling temperature almost instantly. Figure 2a presents experimental data obtained by DANTE Solutions, Inc (former Deformation Control Technology, Inc.) of Cleveland, Ohio, USA using its Ø63.5x127mm probe instrumented with thermocouples [Ferguson 2012]. As seen from the graph, the probe surface temperature dropped below the water boiling temperature in about 5seconds from the beginning of the quench.



a) Quenching in high-velocity IQ system b) Quenching in IQ water tank

Figure 2: Experimental cooling curves obtained using DANTE Solutions probe

2.2 Batch IQ process

When quenching parts in batches in IQ water tanks, the water flow velocity is much less compared to that in high-velocity single-part processing IQ units. The boiling process takes place in the beginning of the quench. However, the non-uniform film boiling mode of heat transfer is absent due to a vigorous agitation of the water and due to a small amount of mineral salts added to water. Figure 2b presents experimental data obtained using the above probe during cooling in the IQ water tank. The heat transfer coefficients during the nucleate boiling mode of heat transfer are very high and very uniform. The probe surface temperature drops very quickly (in about 7 seconds) to a value just above the quenchant boiling temperature. The surface remains at this temperature for about 14 seconds till the nucleate boiling process stops and the convective mode of heat transfer begins. During this period of time, the probe surface temperature decreases gradually to the quenchant temperature. These data confirm the presence of the “shoulder” on the part surface cooling curve during batch intensive quenching. Note that the duration of the nucleate boiling mode of heat transfer during the batch IQ process depends on many factors (the part geometry and dimensions, initial heating temperature, quenchant agitation rate and temperature, additive type, etc.). IQ Technologies has a proprietary software that calculates a duration of the nucleate boiling process depending on the above parameters.

3 Specifics of IQ Equipment Design

Two types of IQ equipment are used for implementing the IQ processes: IQ water tanks for quenching parts in batches and high-velocity IQ units for processing parts one at a time.

3.1 IQ water tanks for batch quenching

An IQ water tank can be a standalone unit, or it can be a part of an integral quench atmosphere furnace. Currently, there are two production IQ batch systems in the field. One is a standalone $23m^3$ IQ water tank equipped with an atmosphere 91x91x122cm box furnace located across the aisle from the IQ tank. The system is installed at Akron Steel Treating Co. of Akron, Ohio, USA. The second system is an integral quenched atmosphere 91x91x181cm furnace with a $42m^3$ IQ water tank built by AFC-Holcroft Co. and installed at Euclid Heat Treating Co. of Cleveland, Ohio, USA. Pictures of the above batch type IQ equipment can be found in references [Kobasko 2010, Aronov 2013]. A very low concentration of sodium nitrite in water is used as a quenchant in both IQ tanks. The IQ tanks are capable of processing loads of up to 1,600 and 2,200kg respectfully. The quenchant agitation rate in IQ water tanks is several times greater than that in a typical oil quenched tank. One of the major requirements for the IQ water tanks is providing very uniform water flow distribution throughout the load which is achieved by the use of a set of baffles installed at the IQ tank bottom. Table 1 presents a few of the many examples of parts successfully processed in IQ water tanks.

Part name	Steel	Benefits obtained
Automotive ball studs	AISI 1045	Ball studs made of plain carbon 1045 steel and intensively quenched have the same fatigue life as standard ball studs made of alloy AISI 8640 steel and quenched in oil.
Cold work punches	S5	Service life of intensively quenched cold work punches made of S5 tool steel improved by at least 2 times.
Castings	AISI 8630	Castings made of 8630 steel demonstrated the same or better mechanical properties as the same forged and oil-quenched parts.
Forged rings	AISI 1045	Forged rings made of 1045 steel and intensively quenched have much less distortion compared to the same rings quenched in oil.

Table 1 Examples of practical applications of batch IQ process

3.2 High-velocity IQ units for single-part quenching

Single-part quenching high-velocity IQ systems include the following major components: a water tank, quench chamber, high-pressure pump, piping, set of valves, flow meters and controls.

High-velocity IQ units have two modes of operation: a) an idle mode when the pump takes the water from the tank and pushes it back into the tank bypassing the quench chamber, and b) a quench mode when the pump pushes the water through the piping into the IQ unit quench chamber and then into the IQ unit tank. IQ unit's valves are adjusted to provide a proper water flow through the quench chamber. The direction of the water flow downstream the pump is controlled by a three-way valve. The IQ unit sequence of operations is the following:

- The IQ unit is at the idle mode of operation when a fully austenitized part is placed into the IQ unit quench chamber.
- The quench chamber is sealed.
- The three-way valve redirects the water flow from the bypass to the quench chamber and the IQ process starts.
- At a predetermined time, optimal for the part geometry and steel type, the three-way valve redirects the water flow back to a bypass to interrupt the high-velocity quench.
- The quench chamber is unsealed and the part is removed to continue cooling in the air.

Currently, there are three production high-velocity IQ systems in the field. One IQ unit is designed for processing a variety of steel products (shafts, gears, etc.) and is capable of quenching the parts with a maximum diameter of 18cm and maximum length of 50cm. The system is equipped with an atmosphere box furnace for austenitizing the parts. The second high-velocity IQ unit is designed for processing long shafts up to Ø5cm and length of 91cm. The system is equipped with a 250kW induction heating station for austenitizing the parts. Both these IQ units are installed at the Center for Intensive Quenching at Euclid Heat Treating Co. The third production high-velocity IQ system was designed for processing automotive torsion bars of up to Ø5cm and length of 140cm and is installed at a production facility in Canada. Pictures of high-velocity IQ systems can be found in reference [Aronov 2013]. Similar to batch IQ equipment, one of the major requirements for the single-part IQ systems is providing a uniform water flow distribution throughout the entire part surface area. In some cases, computational fluid dynamic (CFD) modelling is needed for designing optimal quench chambers for specific parts. Table 2 presents some examples of parts successfully processed in high-velocity IQ systems and the benefits obtained versus conventional oil quenching.

Part name	Steel	Benefits obtained
Automotive coil springs	AISI 9259, AISI 9254	Intensively quenched automotive coil springs have longer fatigue life by13 to 27% compared to the same springs quenched conventionally in oil, while intensively quenched lighter automotive coil springs (made of a thinner wire) have the same fatigue life as standard springs quenched in oil.
Automotive output shaft	AISI 1040	Heavy truck output shaft made of plain carbon AISI 1040 steel and intensively quenched outperformed standard output shaft made of alloy AISI 5140 steel and quenched in oil.
Automotive side pinions	Medium carbon lean alloy steel	Automotive side pinion made of limited-hardenability steel and quenched intensively demonstrated better fatigue performance compared to standard side pinion made of carburized AISI 8620 steel and quenched in oil.
Aluminium extrusion dies	H13	Service life of intensively quenched aluminum extrusion dies made of hot work H-13 tool steel improved by at least 40%.

Table 2 Examples of practical applications of single-part quenching IQ process

4 IQ Case Study On Steel Mill Rolls Made Of Continuously Cast Ductile Iron

Steel mill rolls are commonly made of steel, both plain carbon and high alloy D2 tool steel. Continuously cast ductile iron is a cost saving alternative for the plain carbon steels because it is less expensive, easier to machine and provides excellent wear resistance and anti-galling properties for steel mill rolls. Ductile iron is a ferrous metal alloyed with carbon and silicon. Carbon is added in amounts that exceed the solubility limit in iron and as solidification occurs, excess carbon precipitates out as a graphite nodule. Some carbon remains in solution to form pearlite and the foundry can control the ratio of pearlite to ferrite to produce various grades of ductile iron. Steel mill rolls made of ductile iron are usually quenched in oil or polymer. A most typical steel mill roll failure mode is wear of its surface layer, and/or thermal fatigue cracking. Worn rolls can be re-machined and are put back in the field. Ductile iron is not usually considered to be a good alternative for steel mill rolls made from D2 tool steel because of the concern over the service life, D2 can be heat treated to higher hardness with a deeper heat treated zone. All ductile iron grades have plenty of carbon available to form austenite during heat treatment. The problem is being able to quench the austenite fast enough to form martensite to a depth greater than about 15mm from the outside surfaces. One of the ways to improve ductile iron steel mill rolls wear resistance and, hence their service life, is to increase the part hardened depth and its residual surface compressive stresses. Therefore, steel mill rolls made of ductile iron are very good candidates for the use of the IQ process since the IQ technique provides deeper hardened depth and greater residual surface compressive stresses compared to conventional quenching. Although the IQ process will work well on sand castings, the use of continuously cast ductile iron, versus sand cast ductile iron, insures a higher level of material uniformity and thus part quality.

4.1 Processing of continuously cast ductile iron test samples

To evaluate an effectiveness of the IQ process for steel mill rolls, two cylindrical test samples of Ø76x305mm made of continuously cast Dura-Bar 80-55-06 ductile iron were used. The ductile iron chemical composition is presented in Table 3.

Element	C	Si	Mn	S	P
Percentage	3.7	2.6	0.25	0.025 Max	0.05 Max

Table 3 Ductile iron chemical composition

One test sample was quenched in oil and another test sample was quenched intensively in the above $23m^3$ IQ water tank. Both test samples were austenitized at 870^oC and tempered at 150^oC. Test samples were sectioned for microhardness and microstructure evaluation.

4.1.1 Hardness evaluation results – IQ versus oil quenching

The test sample hardness evaluation results by macrohardness and microhardness testing are presented in Table 4 and Figure 4. The macrohardness test provides a general hardness over a

Hardness measurement method	Location	IQ	Oil quench
Macrohardness 150kg	Surface	55 – 57 Rc	46 – 56 Rc
	Mid radius	47 – 51 Rc	34 – 36 Rc
	Core	33 – 34 Rc	32 – 33 Rc
Microhardness 500g	Surface	56.4 Rc	38.1 Rc
	Mid radius	45.6 Rc	37.5 Rc
	Core	36.0 Rc	41.1 Rc

Table 4 Macrohardness and microhardness testing results

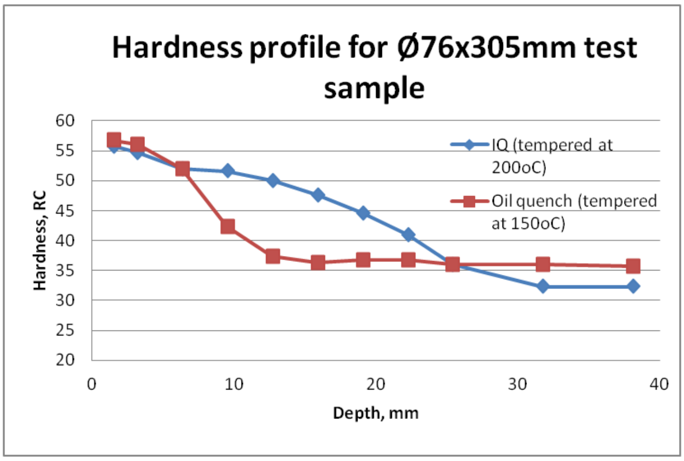
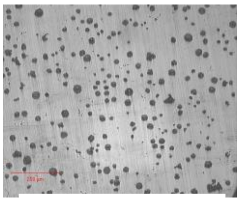


Figure 4: Hardness profile for ductile iron test samples

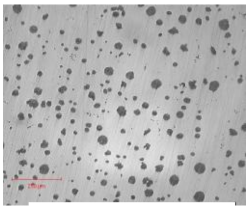
larger area than the microhardness test. The microhardness test allows for more precise matrix hardness testing minimizing the testing effects of the softer graphite particles in the two dimensional plane. The hardness results for the intensively quenched test sample show the positive effects of the IQ process, whereby the hardness is not only higher than after oil quenching but more consistent at all locations. Also, more consistency exists between the macro and microhardness testing. For the oil quenched test sample, the low hardness results obtained by the microhardness testing method compared to the macrohardness method, at all locations, demonstrates the variation in hardness that is obtained with the oil quenching process. Figure 4 presents hardness profiles obtained for the test samples quenched in oil versus quenched intensively. As seen from the graph, the IQ process provides much deeper hardened layer. The hardened depth to a hardness of 50RC for the intensively quenched test sample is two times greater compared to that for the oil quenched test sample.

4.1.2 Microstructure evaluation results

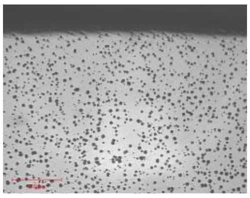
The as-polished samples, as shown in Figure 5, show similar graphite particle size and distribution for both the intensively quenched sample and the oil quenched sample. The etched samples, as shown in Figure 6, show evidence of the quench speed based on the resulting microstructures. The core microstructures both have a bainitic matrix, including some carbides. However, the oil quenched sample microstructure is more representative of upper bainite, while the intensively quenched sample is more representative of lower bainite. The surface microstructure for both the oil quenched sample and the intensively quenched sample are both more representative of a martensitic microstructure, but the surface of the oil quenched sample has more evidence of decarburization and carbide which is magnified by the slower cooling rate of the oil quench. The martensite structure in the intensively quenched sample is more uniform and fine due to the increased cooling rate. There is also evidence of bainite at the surface of the oil quenched sample due to the slower cooling rate.



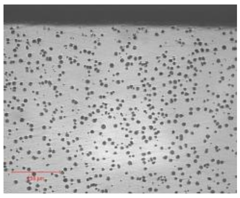
IQ core X100



Oil core X100

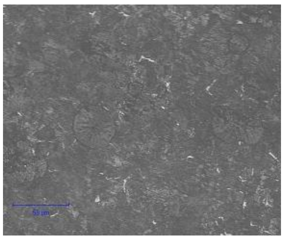


IQ surface X100

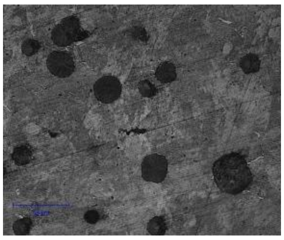


Oil surface X100

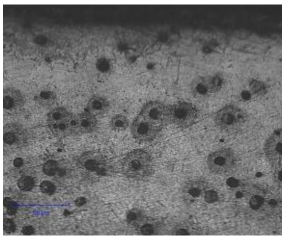
Figure 5: Microstructure for as-polished ductile iron test samples



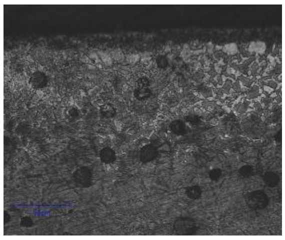
IQ core X500



Oil core X500



IQ surface X500



Oil surface X500

Figure 6: Etched ductile iron test sample microstructure

4.1.3 Residual surface stresses evaluation results

Figure 7 shows a distribution of residual surface stresses obtained by an X-ray diffraction method (the measurements were taken by Proto Manufacturing, Inc. of Taylor, Michigan). Residual stresses were measured down to 3mm from the test sample surface at 5 levels. Results were corrected for stress gradients and material removal as per SAE HS784. As it's seen from the graph, the residual stresses in the sample surface layer are tensile after quenching in oil. While the residual surface stresses for the test sample quenched intensively are compressive within the layer of almost 3mm. The maximum value of residual surface compressive stresses exceeds -275MPA. The residual surface compressive stresses are still high at the depth of 2mm (-200MPA). Residual surface compressive stresses are one of the major factors for improving the roll service life.

4.2 Processing of actual steel mill rolls made of continuously cast ductile iron

The deeper hardness and the high compressive stresses obtained from applying the IQ process to the sample pieces indicated that IQ should improve service life for actual steel mill rolls. Four steel mills provided drawings for their production rolls, ranging in size from a large of approximately 460mm, to medium sized at ~250mm, to small at 50 to 75mm in outside diameter. The large and medium size rolls are usually made from high alloy ductile iron castings, quenched in oil. The small rolls are traditionally made from air-hardened D-2 tool steels. The large, medium and small IQ test rolls were machined from continuously cast low alloy, Dura-Bar ductile iron and intensively quenched. All the IQ rolls were quenched in batches in the 23m3 IQ water tank (Fig. 8). The four steel mill end-users performed field

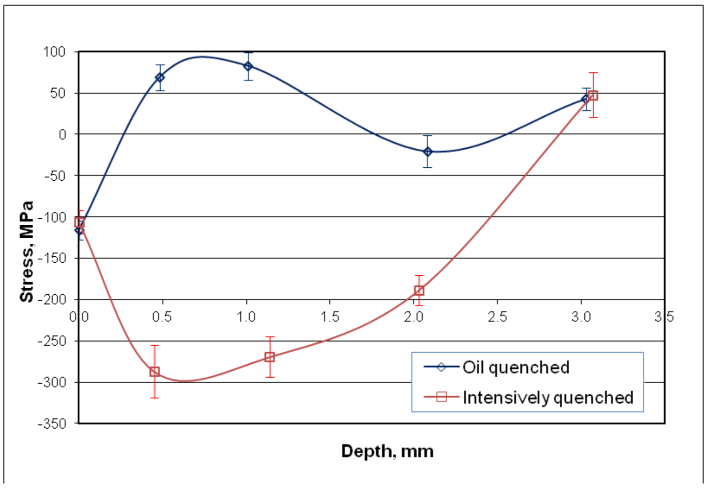


Figure 7: Residual surface stress distribution in test samples

testing on the various sized intensively quenched rolls in actual production conditions at six different steel mills. The results from the mills' field testing indicated that the intensively quenched ductile iron rolls provided service life that was at least equal to the life of the traditionally quenched D-2 rolls and up to two times the service life for the high alloy ductile iron applications. In addition, since the hardened depth on ductile iron from IQ is considerably deeper than traditional oil quenching, the intensively quenched ductile iron rolls can be resurfaced and then put back in service for even longer service life. The field testing also showed that the materials being hot rolled did not stick to the Dura-Bar rolls as readily as to traditionally quenched alloyed cast irons or D-2. Further investigation is being done to quantify the beneficial effect of the lubricity of the graphite particles (and the compressive stresses) in the Dura-Bar material compared to tool steels.

Figure 8: Large rolls on the way into IQ water tank

Figure 9: Examples of steel mill rolls made of ductile iron and quenched intensively

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