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Intensive Quenching Technology For Tool Steels

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Abstract

An extensive experimental and computational study to demonstrate an intensive quenching process for tool steels was conducted. Experiments and calculations were performed for a variety of tool steel products including H-13 steel die-casting machine parts, H-13 steel standard thermal fatigue test block, 52100 steel dies, M2 and S5 steel punches. A proprietary software package for simulation of part quenching conditions was used. Experiments were conducted in both the experimental intensive quenching system and the full-scale production intensive quenching system. Case Western Reserve University of Cleveland, Ohio conducted thermal fatigue testing of the H-13 test block in its foundry facility. The results of these experiments clearly demonstrated the benefits of the intensive quenching technique for tool steels: increased surface and core hardness, increased hardened layer, improved part microstructure, improved strength properties of the steel parts, and part service life.

Keywords

Intensive quenching, water quenching, tool steels.

Introduction

The IntensiQuench[SM] process has been validated by hundreds of laboratory and field experiments for a variety of steels and steel products. Below, we presented several case studies conducted for tool steel products including some examples from recent demonstration projects in the U.S. The part suppliers performed all metallurgical analysis and fatigue testing. Case Western Reserve University (CWRU) of Cleveland, Ohio performed some metallurgical tests.

Case Study for S5 Steel Punches

The main material properties that determine the performance of the punch are toughness, strength and wear resistance. The strength and toughness are critical in preventing cracking and chipping of the punch under the severe impact of this fabrication process. The wear resistance is required to preserve the cutting edges of the punch, thereby maintaining constant processing parameters and ensuring the dimensional accuracy of the holes. All of these critical properties are affected by the cooling rate during quenching. A faster cooling rate should permit higher hardness levels without compromising the toughness of the punch.

Presently, tool steel punches are oil quenched and tempered. While the performance of the punches is satisfactory, the manufacturer is interested in further improving the useful life of the punches by utilizing a faster cooling rate during the quenching process. The objective of this study was to demonstrate the superior performance of punches quenched by the IntensiQuench[SM] process. During processing the parts are submersed in fast flowing water quenchant, yielding very fast cooling rates, and then the intensive quench is "interrupted" when the compressive surface stresses are at their maximum value. In addition to the microstructural benefits to the punch from the fast cooling rate, the IntensiQuench[SM] process also generates high compressive stresses at the surface that minimize the risk of quench cracking and extend the useful life of the punch.

Experimental Study on Punch Samples

An experimental program was initiated to evaluate the effect of IntensiQuench[SM] process on the properties and performance of S5 steel for punches. Two commercial heat treaters, a punch manufacturer and CWRU joined the program.

Cylinders of 38 mm (1.5”) diameter and 56 mm (2.2”) long and punches machined from the same steel batch were quenched in oil and by the IntensiQuench^{SM} process. The oil quenching was conducted on batches of punches heated in a vacuum furnace with a rapid transfer mechanism to an integral oil quench tank. The IntensiQuench^{SM} process was performed in water on individual cylinders and punches in our experimental quenching system described in References 1 and 2 using the IQ-3 quenching method. In this process, the part is submersed in a flow of water, yielding very fast cooling rates of about 90^{o}C/sec at the surface of the cylinder. Quenching was interrupted when surface compresses stresses reached their maximum value. Charpy V-notch samples were cut from the as-quenched and tempered cylinders and evaluated. Hardness measurements were taken from Charpy V-notch samples cut from the cylinders. The distortion of the cylinders was mapped with a Coordinate Measuring Machine. The depth profile of the residual stresses in the surface region of the cylinders was measured by X-Ray diffraction methods. The X-ray diffraction residual stress measurements were made from the surface to a nominal depth of 0.5mm in approximate increments of 50 x 10^{-3} mm.

Table 1 presents the hardness measurements of cylindrical punch samples that were intensively quenched and quenched in oil.

Table 1 Hardness of Cylinder

Cylinder #	V-notch Sample #	Hardness, HRC
Oil Quenching		
1	1	60.5; 60.1; 60.1
	2	60.1; 60.2; 60.2
	3	60.0; 60.4; 60.5
	4	60.2; 60.8; 60.7
2	1	60.8; 60.6; 60.8
	2	60.8; 60.7; 60.4
	3	60.8; 60.9; 60.9
Average Hardness		60.5
Standard Deviation		0.31
Intensive Quenching		
3	1	60.6; 61.0; 60.5
	2	61.0; 61.0; 61.2
	3	61.1; 61.4; 61.2
4	1	61.1; 61.3; 61.3
	2	60.4; 60.8; 60.7
	3	60.0; 59.6; 59.9
	4	59.4; 59.5; 59.9
Average Hardness		60.6
Standard Deviation		0.65

The hardness of cylinders quenched in oil from 900^{o}C (1650^{o}F) was 62-63 HRC while the hardness of intensively quenched cylinders from the same temperature was 63-64 HRC. After three hours tempering at 300^{o}F the hardness of all the cylinders was 60-61 HRC. Hardness measurements were also taken from fourteen Charpy-V-notch samples cut longitudinally from the cylinders.

While the as-tempered average hardness of all the cylinders was practically identical, the oil-quenched specimens were more uniform in hardness with a standard deviation of 0.3 HRC versus a standard deviation of 0.6 in the hardness of the intensively quenched samples. This difference is attributed to the faster heat removal in IntensiQuench^{SM} process, which generates a faster cooling rate at the surface relative to the center of the cylinders. The hardness at the surface (with the compressive stresses) therefore tends to be slightly higher than in the center.

The toughness levels measured up to 100^{o}C for the cylinders quenched by the IntensiQuench^{SM} process were higher than the toughness of the oil quenched cylinders for similar hardness values although both were relatively low because of the high carbon and hardness values of both sets of punches. The average energy absorbed by the oil quenched Charpy V-notch samples at room temperature was 1.36 N·m (1 ft·lb) versus 4.08 N·m (3 ft·lb) for the intensively quenched sample. At 100^{o}C the average energy absorbed by the oil quenched Charpy V-notch was 3.4 N·m (2.5 ft·lb) versus 6.12 N·m (4.5 ft·lb) for the intensively quenched sample. The higher toughness at similar hardness levels is an indication of superior performance. It means the intensively quenched punch should have more resistance to chipping. Alternatively, intensively quenched punches should be tempered to higher hardness, while still maintaining acceptable toughness levels. This in turn should improve the wear resistance of the punch relative to an oil-quenched punch.

The difference in quenching rates between the oil and the IntensiQuench^{SM} process also affects the distortion patterns of the cylinders. The distortion map of an oil-quenched cylinder shows that the cylinder is bulged around the center perimeter, with the center diameter about 0.081 mm (0.0032”) *larger* than the top and bottom diameters. The distortion map of an intensively quenched cylinder shows that the cylinder has an “hourglass” shape, with the center diameter being about 0.081 mm (0.0032”) *smaller* than the sides. These differences can be explained by considering the dimensional changes during the phase transformation. The rapid cooling rate during

IntensiQuench^{SM} process quickly forms a hard and stiff "shell" of martensite over the entire surface of the cylinder. The expansion associated with the martensitic transformation causes high compressive stresses at the surface, which are partially accommodated by this change in shape. The top and bottom of the cylinder expand pushing the adjacent shell outward. At the same time, the longitudinal expansion at the surface is pushing the top and bottom shell perimeters outward.

In the oil-quenched cylinder, the strong martensitic layer does not form as quickly. When the core transforms and expands, it can still push the surface layer of the cylinder out, causing it to bulge. These differences are significant in two aspects. The first aspect concerns the dimensional control of the punches, which has to be kept within tolerance. The second aspect relates to the residual stresses. It was anticipated that the IntensiQuench^{SM} process would generate higher compressive stresses in the surface thus minimizing the risk of cracking during the quench and enhance the performance of the punch in use. The distortion pattern (mapped at Case Western Reserve University) indicates that this is indeed the case.

The axial and circumferential residual stress distributions measured as functions of depth are shown graphically in Fig. 1 and Fig. 2. Compressive stresses are shown as negative values, while tensile stresses are shown as positive, in units of MPa. The X-Ray residual stress measurements detected axial and circumferential compressive stresses of -900 MPa at the surface of the intensively quenched cylinders. In the oil quenched cylinders tensile residual stresses of about 200 MPa were measured. For cylindrical samples from which complete shells were removed by electropolishing for subsurface measurement, the radial stress is calculated assuming a rotationally symmetrical residual stress distribution.

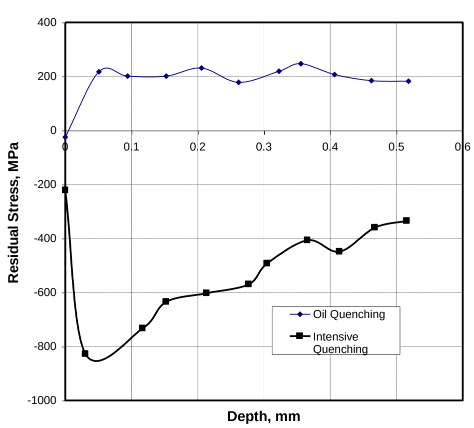

Figure 1 Punch Axial Residual Stresses

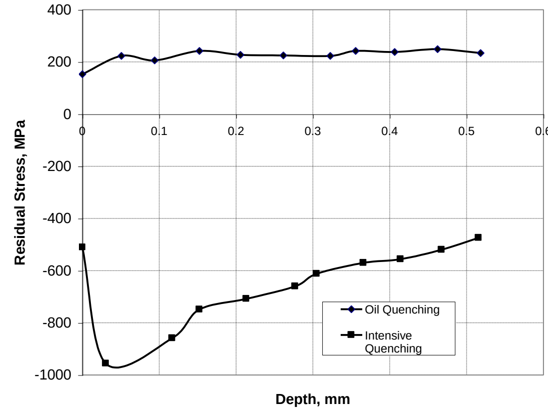

Figure 2 Punch Circumferential Stresses

Table 2 below summarizes the punch properties improvements due to the intensive quenching process.

Table 2 Improvement of S5 Steel Punch Sample Properties *

Property		Oil Quench	Intensive Quench
Hardness, HRC	As quenched	62-63	63-64
	After temper	60-61	60-61
Impact strength, N·m	@72^{o}F	1.36	4.08
	@100^{o}C	3.4	6.12
Residual stresses, MPa		200	-900

*As measured by Case Western Reserve University.

Punch Service Life Improvement Field Evaluation

To evaluate punch service life improvement, twelve 17.5 mm (11/16") square S5 steel punches (Fig. 3) were intensively quenched and put in "production" conditions.

Figure 3 S-5 Steel 17.5x17.5 mm Square Punch

The punches were heated to austenite temperature in a neutral salt bath furnace and quenched in batches (six punches per batch) in the intensive quenching experimental system. Twelve identical punches made from the same steel heat were oil quenched in accordance with the current technology and also put in the field conditions. The oil-quenched punches were heated prior to quenching in a vacuum furnace.

In the field-testing, the punches punched 17.5 mm (11/16”) holes through 15.9 mm (5/8”) and 19.1 mm (¾”) thick 1085 steel material using a 19.1 mm (¾”) square female die in a single station 250-ton mechanical press. “Service life” (as defined by the punch user) is when chipping or wear is “excessive” and the punched holes are no longer acceptable. The press cycled every 15 seconds. Oil quenched punches lasted approximately 1 hour and made on the average approximately 450 holes in the 1085 material. While intensively quenched punches lasted approximately 2 hours and made on average approximately 900 holes. Thus, the IntensiQuench^{SM} process improved the service life of the S-5 punches by about two hundred percent or two times.

High Speed Punches and Dies Service Life Evaluation

Dr. Kobasko conducted a service life evaluation study for high-speed round punches at a tool product manufacturing plant in Bulgaria. The punches were made of R6M5 steel (very close in chemistry to AISI M2 steel) and had the following dimensions: 15.3 mm (0.6”) diameter and 126 mm (5”) length. These punches were used at high loads in an automatic punch press machine with the capacity of 175 strokes per minute. Seven punches were intensively quenched and seven punches made from the same steel heat were quenched in accordance with the current technology. Both sets of punches were heated up prior to quenching in a high-temperature salt bath furnace. Table 3 presents the field test data. As seen from the data, the IntensiQuench^{SM} process improved the average “service life”* by about 2.5 times. The reason for the improved performance is attributed to increased material toughness and residual surface compressive stresses from the intensive quenching process.

Case Study for H-13 Steel Aluminum Die Casting Dies

Heat treaters know that the higher the cooling rate during quenching the “hot-work” die steels the greater the part thermal fatigues resistance when in service. To prove that the intensive quenching technique provides better thermal fatigue resistance and toughness in die casting dies, CWRU and IQ

Table 3 High-Speed Punch Service Life Improvement

Test #	Number of Strokes* (*until punched holes are no longer functionally acceptable in size or shape)		Increase in # of Punched Holes Life, Times
	Existing Technology	Intensive Quenching	
1	6460	15,600	2.4
2	6670	16,500	2.5
3	3200	5,300	1.7
4	4000	12,075	3.0
5	6620	8,110	1.2
6	2890	10,500	3.6
7	2340	7,300	3.1

Technologies intensively quenched standardized 50mm×50mm×178mm test blocks made of H-13 hot-work die steel. H-13 steel is widely used for aluminum die casting tools in the U.S. In die casting of aluminum parts, the dies (and gating for channeling the molten aluminum into the die cavity) must repeatedly withstand temperatures of over 1,000 degrees F. After taking a shot of molten aluminum the H-13 tooling undergoes a rapid cooling cycle from the internal water-cooling passages. The water-cooled dies help the aluminum cast part to solidify and become dimensionally stable so the whole process can be repeated. Since molten aluminum has the viscosity of water, the die casting dies must also contain high pressures without distortion.) A duplicate set of test blocks were also made from the same lot of H-13 steel, but quenched in oil. (The usual hardening practice for H-13 steel is to air quench or to gas pressure quench the die in a vacuum furnace.)

The thermal fatigue properties for both the intensively water quenched and the oil quenched H-13 steel test blocks were evaluated by means of a thermal fatigue test methodology developed by CWRU. This test determines the average maximum crack length and total crack area on the four corners after a certain number of cycles of “in process” heating (by immersion into a bath of molten aluminum at 732°C) and cooling (by coolant flow within the test block’s internal water passage). Therefore, just as H-13 aluminum die casting dies in production situations, the test blocks have a high thermal gradient throughout the test block cross-section, especially severe at the test blocks’ corners. This test simulates the cyclic heating and cooling found in aluminum die casting dies made of H-13 material. (It should be noted there were no cracks present in any of the intensively or oil hardened H-13 test blocks at the inception of the cyclic testing.)

Figure 4 and 5 show the effect of thermal cycles on the average maximum crack length and on total crack area. As shown, there is practically no difference in these two parameters for both tests

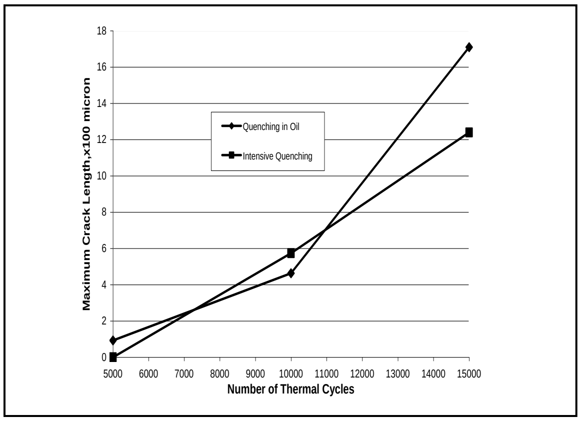

Figure 4 Maximum Crack Size vs. Number of Thermal Cycles

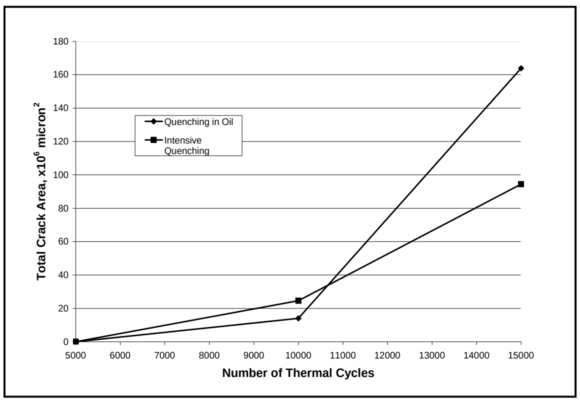

Figure 5 Total Crack Surface Area vs. Number of Thermal Cycles

blocks for 5,000 and 10,000 thermal cycles. However, there is a significant difference between these parameters for 15,000 thermal cycles. The average maximum crack length for the intensively quenched test block is about 27% less than for the oiled quenched test block. The total crack area for the intensively quenched test block is about 42% less than for the oiled quenched test block. Since this test correlates with the actual service life of H-13 dies (albeit conventionally air hardened), the test indicates even greater service life for intensively quenched dies made of H-13 steel. Several of intensively quenched H-13 dies and die components are currently undergoing in service field-testing and evaluation.

Summary of IQ Process Benefits

IntensiQuench[SM] processes, IQ-2 and IQ-3, work well with practically all steel products including typical tools and dies made of various tool steel types to enhance fatigue resistance, improve wear, while at the same time minimizing distortion and providing higher hardness and increasing beneficial compressive surface stresses. IQ Technologies, Inc. offers computer process modeling and proven design tools for implementing intensive quenching technology upon a wide variety of steel alloys in various part geometry. Manufacturers of steel parts can improve their product quality and reduce cost utilizing IQ Technologies' proprietary software and processes. Some of the specific, proven advantages of intensive quenching detailed in this article include:

⇒ Elimination of cracking during quenching
⇒ Minimum 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 (enhanced value engineering)
⇒ Replacement of hazardous quench oil with environmentally friendly water or polymer/water solutions
⇒ Better integration of the heat-treating process into the production process flow.

Acknowledgement

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