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Local Film Boiling and Its Impact on Distortion of Spur Gears During Batch Quenching

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ABSTRACT: The paper discusses results of computer simulation connected with the double distortion during batch quenching of spur gears caused by a local film boiling between teeth. A carburized gear, outside diameter 2.5 in., was intensively quenched in conditions that provided heat transfer coefficient (HTC) equal to 25 000 $Wm^{-2}K^{-1}$. In some places between teeth local film boiling took place where HTC was 800 $Wm^{-2}K^{-1}$. Computer simulation showed that maximum displacement is observed between teeth where local film boiling took place. The authors came to the conclusion that increasing critical heat flux densities and elimination of local film boiling can result in decreasing distortion of spur gear. That is true for different sizes of gear during their quenching when using the second type of intensive quenching process (IQ-2) technique (a two or three-step quenching process). It is underlined that critical heat flux densities have a great effect on distortion during batch quenching. The authors also came to the conclusion that a small amount of special additives can decrease significantly distortion during quenching of gears. That is why a global database on cooling capacity of quenchants should be available which must contain critical heat flux densities of different kinds of quenchants.

KEYWORDS: computer simulation, displacement, critical heat flux density, local film boiling, additives, spur gear, IQ-2 process, optimization

Introduction

The paper discusses double distortion during batch quenching of gears caused by local film boiling between two teeth. Double distortion means that the top of each tooth moves in opposite direction when between two teeth a local film boiling takes place. Computer simulation showed that such behavior of teeth generates two times larger distortion. The present work is the second part of the authors' investigations. The first part was discussed at the World Scientific and Engineering Academy and Society (WSEAS) Conference held on August 20–22, 2010 in Taipei, Taiwan [1]. On the basis of experiments, computer fluid dynamics (CFD) modeling, and finite elements method (FEM) calculations of residual stress distribution in gears, the authors came to the conclusion that distortion and variations in dimensional change can be significantly decreased by combining water flow velocity with special chemical additives, which increase the first critical heat flux density [2,3]. During batch quenching of large gears in an agitated, anticorrosion water-salt solution of optimal concentration, distortion variation is small and dimensional change is repeatable from tooth to tooth. During intensive quenching of small gears in a high velocity intensive quenching (IQ-3)

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system distortion sometimes is not repeatable, especially when local film boiling occurs between gear teeth. Computer simulation shows that double distortion (twice as much distortion) can occur when local film boiling takes place between two adjacent teeth. Several measures have been addressed to decrease distortion variation, namely to optimize the concentration of brine solution. Investigations of critical heat flux densities and local film boiling can result in decreasing distortion of steel parts during quenching. Unfortunately, in heat treating industry there are no data on critical heat flux densities; no standard on their correct measurement and testing quenchants with special additives. Computer simulation showed that such data should be available for engineers to optimize distortion of steel parts during quenching.

IQ-2 Technological Process

An IQ-2 technique (a two or three-step quenching process that initially cools parts under the nucleate boiling mode of heat transfer and then by convection) is often used for quenching of gears. The first step of the IQ-2 process involves intensive cooling without film boiling until a superficial layer of the part being quenched contains 50 % martensite. At this point, the intensive cooling process is interrupted; steel parts are removed from the quench and cooled in the air. During this period of time, the temperature is equalized throughout the part cross-sections and self-tempering of the newly formed martensite in the superficial layer occurs. Then the parts are moved back to the quench, and intensive cooling continues until the martensite transformation is completed, or until parts are cooled completely to room temperature in the air. However, it is very difficult to eliminate a local film boiling, which can take place between teeth during batch quenching. Usually, local film boiling is observed when initial heat flux density is equal to the first critical heat flux density q_{cr1}.

The IQ-2 quench method is suitable for a variety of steel products, including automotive and off-highway equipment components (gears, coil springs, kingpins, torsion bars, bearing products, ball studs), fasteners of different types, and tool products (punches, dies, die components). For intensive quenching of steel parts, different IQ-2 systems were designed and built (see Figs. 1 and 2).

Akron Steel Treating (AST) company has one production 6000-gal IQ water tank that is equipped with an atmosphere Surface Combustion furnace. AST has fully automated the IQ water tank and modified the load lifting mechanism to reduce the time required for loading/unloading

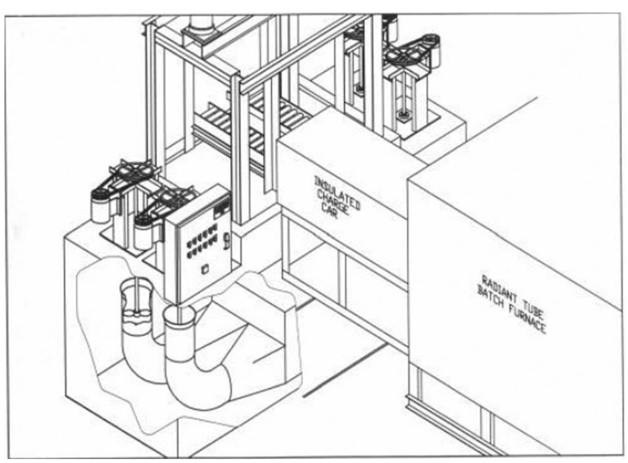

FIG. 1—*Layout of production IQ system installed at Summit Heat Treating Co. (AST) [2].*

FIG. 2—*Production IQ system installed at Euclid Heat Treating Co. [2].*

the parts during intensive quench. AST also developed a standard procedure for controlling the concentration of the sodium nitrite in the IQ water tank, water temperature, and rate of the quenchant agitation. A full automation of the IQ water tank and a precise control of the quench parameters allow intensive quenching of a variety of steel products in the production IQ system.

AST runs several jobs from three its customers on a continuous basis. These jobs are the following:

- Gear blanks made of alloy 4140 and 4340 steel for manufacturing rack and pinion gears
- Shafts made of carburized steel
- Stampings made of carburized steel
- Punches made of AISI S5 steel
- Dies made of AISI H13 steel
- Chisels made of AISI 1045 and 4340 steels
- Kingpins, etc.

Euclid Heat Treating Co. bought its first IQ production unit from AFC-Holcroft, Inc. in 2003. It is a three-chamber, integral quench, batch-type furnace with working dimensions of 91 cm × 91 cm × 183 cm (36in. × 36 in.× 72 in.) for implementing the batch IQ process. The new system is used now for:

- Quenching of big gears
- Different plates made of alloy and plain carbon steels
- Dies made of AISI H13 steel
- Chisels made of AISI 1045 and 4340 steels
- Big forgings, etc.

In many cases the shortcoming of this system is distortion of steel parts during batch quenching. That is why the goal of our investigation is to find out how local film boiling impacts distortion of spur gears. Prior to making calculations let us consider the importance of critical heat flux density values.

FIG. 3—*Cylindrical steel parts prepared for batch quenching using IQ-2 technology.*

Importance of Critical Heat Flux Densities

The critical heat flux densities q_{cr1} and q_{cr2} are inherent properties of any vaporizable quenchant. The first critical heat flux density (q_{cr1}) is the maximum amount of thermal energy coming out of a unit of surface area needed to create film boiling in the given liquid over a hot surface area. The more resistant a liquid is to boiling when heat is applied, the higher the liquid's q_{cr1} is [2]. The more resistant a quenchant is to boiling, the more likely it is to quench a part uniformly (with no film boiling), thus yielding less distortion. Also, with greater resistance to boiling, there is less likelihood of a "slack quench"—a quench that is sufficiently slow to produce spotty or lower than optimum as-quenched hardness for a given steel alloy. On the other hand, the second critical heat flux density (q_{cr2}) is the minimum amount of heat energy necessary to support film boiling over the given surface area. A scheme of heat transfer modes during quenching of steel parts is shown in Ref [2].

The following experimental correlation between q_{cr2} and q_{cr1} is used [2]

$$\frac{q_{cr2}}{q_{cr1}} \approx 0.2 \tag{1}$$

To predict modes of heat transfer, the first critical heat flux density should be compared with the initial heat flux (q_{in}) at the moment of immersion of steel part into quenchant. The initial heat flux density (q_{in}) means the heat flux that appears during immersion of steel parts into quenchant. It depends on configuration and size of steel part, thermal properties of the material, and

TABLE 1—*Pool film boiling of water on spheres [4].*

Sphere Material	Diameter, mm	Water Subcooling, ΔT_{sub}	HTC, W/m^2K	Number of Observation
Stainless steel	19	0	243–252	4
Stainless steel	19	30	351–360	3
Stainless steel	19	50	520–545	2
Stainless steel	25.4	0	223–249	7
Stainless steel	25.4	30	417–440	5
Silver	19	0	230–260	6
Silver	19	30	436–466	5

TABLE 2—*Forced flow film boiling of water on 19 mm diameter AISI 304 stainless steel sphere [4].*

Water Subcooling ΔT_{sub}	Water Flow Velocity, U (m/s)	HTC_{min}, W/m^2K	Minimum Film-Boiling Temperature, $(\Delta T)_{min}$	Number of Observation
0	0.02	233–261	114–120	3
0	0.45	460–480	126–127	2
30	0.02	440–457	334–344	2
30	0.45	940–960	328–346	3
50	0.02	540	469–474	2
50	0.45	1070–1100	469–484	4

austenitizing temperature. It could have any of three variants of such comparison: $q_{in} > q_{cr1}$; $q_{in} < q_{cr1}$; $q_{in} \approx q_{cr1}$.

When $q_{in} > q_{cr1}$, full film boiling is established around the steel part (for example gear) and smooth cooling is provided in this case. Distortion of steel part (gear) will be minimum due to smooth cooling, however surface hardness and depth of hardened layer will be minimum too because of very slow cooling during smooth film boiling. Only high alloy steels can be quenched properly by using this method of cooling.

When $q_{in} < q_{cr1}$, full film boiling is absent around the steel part (for example gear) and smooth cooling is provided by transient nucleate boiling process. Distortion of steel part (gear) will be similar to oil quenching, however surface hardness and depth of hardened layer will be maximum because of a very high cooling rate during nucleate boiling. In this case high alloy steels can be substituted with lower alloy steel or plain carbon steel. Size of steel part after intensive quenching slightly changes due to more complete martensite transformation.

If $q_{in} \approx q_{cr1}$, local film boiling is observed on the surface of steel parts. During batch quenching of cylindrical steel parts (for example chisels), local film boiling can be inside the load and leads to great distortion of the chisels. To eliminate this effect, heat treaters try to separate chisels far from each other to provide enough room between chisels that decreases the probability of local film boiling. Such a load, prepared for batch quenching, is shown in Fig. 3.

Dhir and Purohit developed the theory and accurate method for measuring experimentally pool film boiling of water on spheres [4]. Results of their investigations are provided in Table 1 and Table 2. It is well known that during quenching of plates film boiling is more stable and the heat transfer coefficient (HTC) has less value as compared with the quenching of spheres.

On the basis of experimental results obtained, it makes sense to consider HTC during local film boiling as 800 W/m^2K for poor cooling of teeth, which is the reason for large distortion of gears during batch quenching. Other areas of the gears are cooled intensively where HTC of 25 000 W/m^2K is provided. These values are taken into account based on experimental data and CFD modeling [2,4].

Impact of Local Film Boiling on Distortion and Residual Stresses After Batch Quenching

Impact of local film boiling on distortion and residual stresses after batch quenching was investigated by DANTE software, which allows receiving also metallurgical data like amount of martensite, bainite, etc. For computer FEM modeling a gear, shown in Fig. 4, was used. The maximum outer diameter of the spur gear shown in Fig. 4 is 63.5 mm. The gear has 28 teeth and has a common configuration that is often used in machine building.

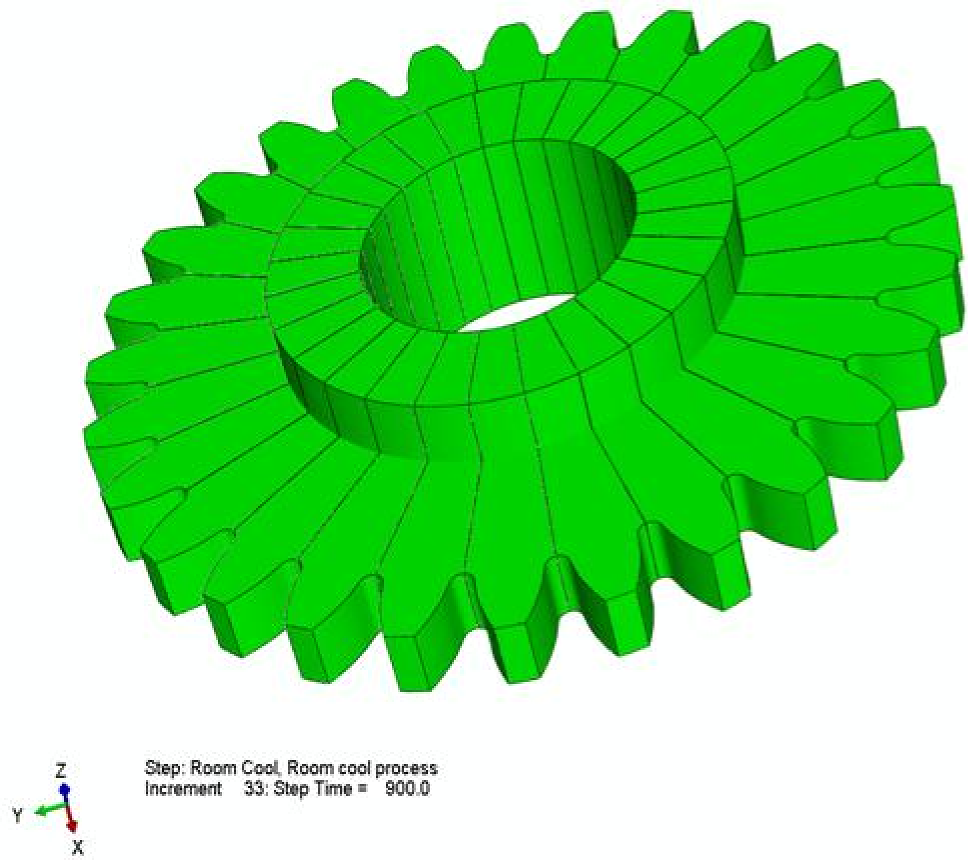

FIG. 4—*A spur gear made of AISI 8620 steel.*

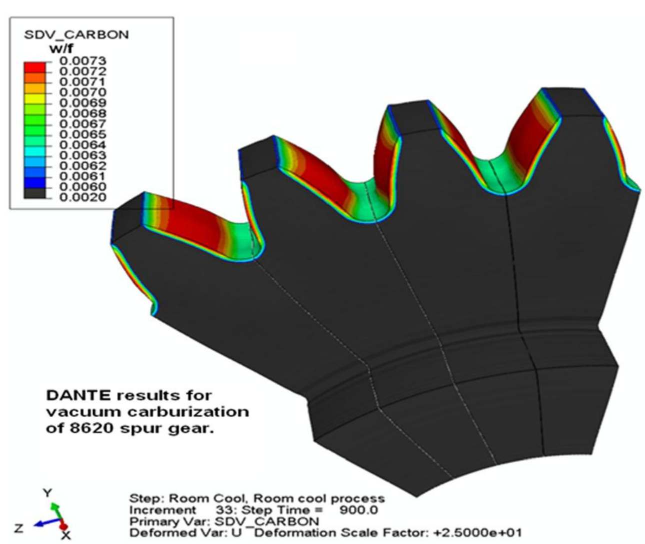

FIG. 5—*Carbon content in spur gear after vacuum carburization (only flank faces and root were carburized).*

During the batch quenching, many gears are located near each other and quenched in agitated cold water or water-salt solution of optimal concentration. As a result of the proximity of gears, local film boiling as a rule is observed between teeth that are directed perpendicular to the liquid stream. Agitation of water increases the first critical heat flux density, however it cannot be increased enough and can be equal to q_{cr1}, which creates conditions for local film boiling. Small amount of additives, dissolved in the quenchant, can eliminate film boiling and decrease distortion.

Only functional surfaces were carburized, i.e., flank faces and root.

It was established by experiment that distortion depends on thickness of the carburized layer. This problem will be considered in detail by the authors later when more experimental data are collected and more computer simulations are done. Thickness of the carburized layer and content of carbon in it affect distortion because of changing specific volume of martensite and current stress distribution. As one can see from Fig. 5, the content of carbon in the carburized layer was within 0.6 %–0.73 % and in other areas content of carbon was 0.2 %.

As is known, the martensite start temperature M_S depends on content of carbon in steel. The higher the carbon in steel is, the lesser is the martensite start temperature M_S. For example, for AISI 8620 steel the martensite start temperature is about 405°C (760°F), see Fig. 6. For AISI 8660 steel the martensite start temperature drops to 260°C (500°F), see Fig. 7. For high carbon steels the martensite start temperature could be equal to the boiling point of liquid.

For a given content distribution in the gear (see Fig. 5), computer simulation was performed with existing poor cooling between some teeth. The red areas of the gear (see Fig. 8) show poor cooling caused by local film boiling, which differs from transient nucleate boiling by almost 31 times.

Each red area in Fig. 5 shows poor cooling where during local film boiling heat transfer coefficient (HTC) is 800 $Wm^{-2}K^{-1}$ (see Table 1 and 2). Other areas of gear are cooled intensively where average effective HTC is equal to 25 000 $Wm^{-2}K^{-1}$. Average effective HTC is significantly less as compared with real HTC because heat flux density is divided by $T_{sf} - T_m$.

Here $T_{sf} - T_m \gg T_{sf} - T_S$; T_S is saturation temperature (boiling point) [6]. The real HTC is calculated as $q/(T_{sf} - T_S)$ [6].

For calculating distortion and residual stresses a sector of a gear was considered (see Fig. 9). At each time and space step, the calculation results were compared with the continuous cooling

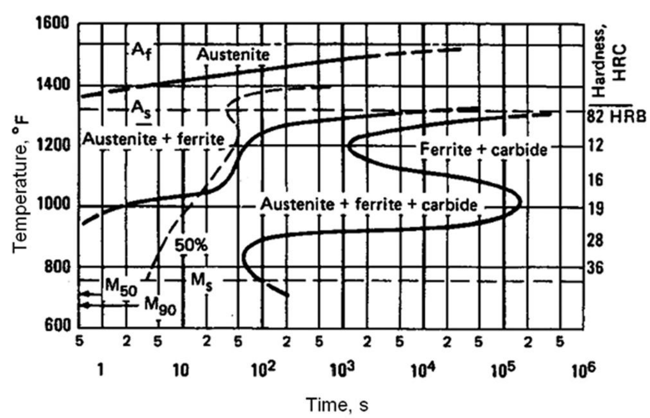

FIG. 6—*Isothermal transformation diagram for AISI 8620 steel austenitized at 900°C (1650°F). Composition: 0.18 C; 0.79 Mn; 0.52 Ni; 0.56 Cr; 0.19 Mo. Grain size 9 to 10 [5].*

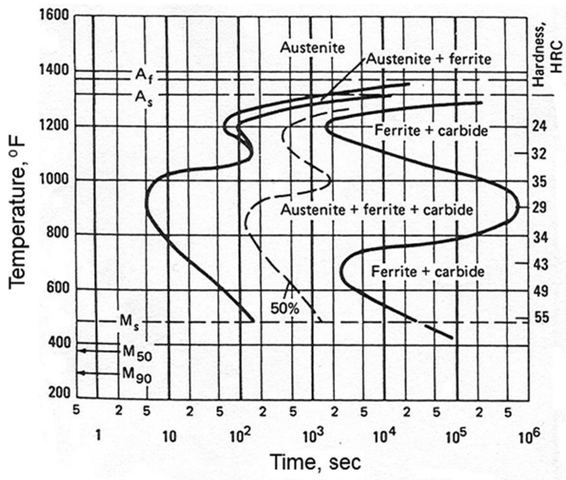

FIG. 7—*Isothermal transformation diagram for AISI 8660 steel austenitized at 845°C (1555°F).Composition: 0.59 C; 0.89 Mn; 0.53 Ni; 0.64 Cr; 0.22 Mo. Grain size 8 [5].*

transformation (CCT) diagram of the supercooled austenite to choose appropriate thermal and mechanical properties depending on temperature. For boundary conditions average effective HTC of 25 000 W/m^{2}K for boiling process and 800 W/m^{2}K for local film boiling process were used.

The process of calculation was within the austenitizing temperature and room temperature. Such an approach can be explained by the following. After a certain intensity of quench heat extraction, the thick part of a gear cannot give up its heat any faster than the rate of heat conduction through the part. This is why one cannot quench "too fast" during the intensive portion of the quench. Once the part surface layer has reached the temperature of the quenchant, conduction within the part sets a natural limit on the rate of cooling in the subsurface layers and the core of the part. Because conduction is also a very rapid and very uniform form of heat removal, intensive quenching is able to reach the ultimate goal of any quench—the most uniformly rapid removal of heat that yields the less part distortion.

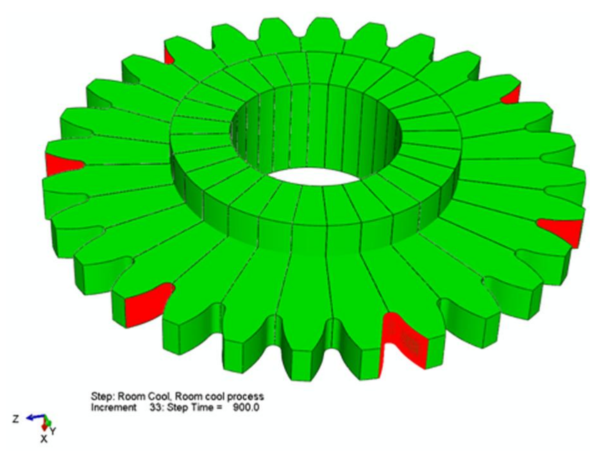

FIG. 8—*Red areas of gear show poor cooling caused by local film boiling.*

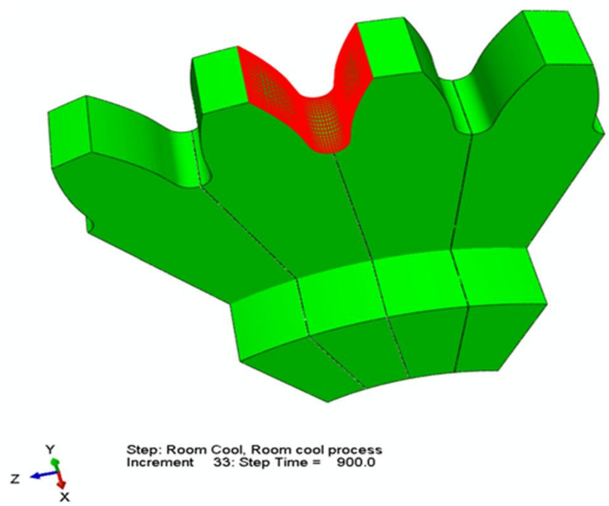

FIG. 9—*The area of a gear for meshing and FEM calculations the stresses and distortion.*

When quenching large gears in agitated water or water-salt solutions, convection can prevail. The criterion, which provides direct convection, is [2,3]

$$Bi = \frac{2(\vartheta_0 - \vartheta_I)}{\vartheta_I + \vartheta_{uh}} \tag{2}$$

The value ϑ_I is calculated from Eq 3

$$\vartheta_I = \frac{1}{\beta}\left[\frac{2\lambda(\vartheta_0 - \vartheta_I)}{R}\right]^{0.3} \tag{3}$$

$$\beta = \frac{75\lambda'(\rho' - \rho'')^{0.5} g^{0.5}}{\sigma^{0.5}(\rho'' r^* \bar{W}'')^{0.7}\,\mathrm{Pr}^{0.2}} \tag{4}$$

where:

λ is thermal conductivity of steel (W/mK)
R is radius or half thickness of plate shaped steel parts
$\vartheta_0 = T_0 - T_S$,
$\vartheta_I = T_I - T_S$,
$\vartheta_{uh} = T_S - T_m$,
T_0 is initial temperature,
T_I is initial temperature of the surface at the beginning of nucleate boiling,
T_m is temperature of a quenchant (liquid),
$\mathrm{Pr} = \frac{\nu}{a}$ is Prandtl criterion (dimensionless number),
ν is kinematic viscosity (m^2/s),
λ' is thermal conductivity of the liquid (W/mK),
σ is surface tension (N/m),
g is acceleration due to the gravitational force (9.8 m/s^2),
ρ' is liquid density (kg/m^3),

ρ'' is vapor density (kg/m^3),
r^* is latent heat of evaporation (J/kg), and
W'' is vapor bubble growth rate (m/s).

As one can see from Fig. 10, a more complete martensite transformation occurs in non-carburized AISI 8620 steel, where 99 % martensite is formed. In the carburized layer, where content of carbon is 0.60 %–0.73 %, only 90 %–96 % of martensite is formed.

As a result of local film boiling and a low HTC, the transformation of austenite to martensite is delayed in the area where film boiling takes place. The transformation starts first on the left side of tooth 1 and on the right side of tooth 2, as shown in Fig. 10. Because a specific volume of the martensite is greater than that of austenite by 4 %, the surface layers during quenching expand, causing the movement of tooth 1 to the right and tooth 2 to the left. This tooth movement generates residual compressive stresses at the root area and near it (see Fig. 11) resulting in double distortion between them. Note that in Fig. 11, S22 means axial residual stresses. The hoop stresses are designated as S33, and radial as S11 [2].

The distribution of minimum and maximum principal stresses in spur gear after batch quenching and double distortion are presented in Fig. 12 and 13. Similar to S22 stresses, the larger principal compressive residual stresses are observed between tooth 1 and tooth 2 (see Fig. 12 and 13).

In Fig. 14 the total displacement between two teeth where local film boiling took place is presented.

On the basis of investigations concerning the effect of local film boiling on distortion of gears, our main recommendations are as follows:

To introduce widely an intensive quenching IQ-2 technology into the heat-treating practice, first of all, special additives should be developed to increase the first critical heat flux density that can prevent local film boiling effectively and thus decrease distortion of steel parts.

It is important to apply IQ-2 processes in captive heat treating shops where mass production exists that can be completely automated and carefully controlled.

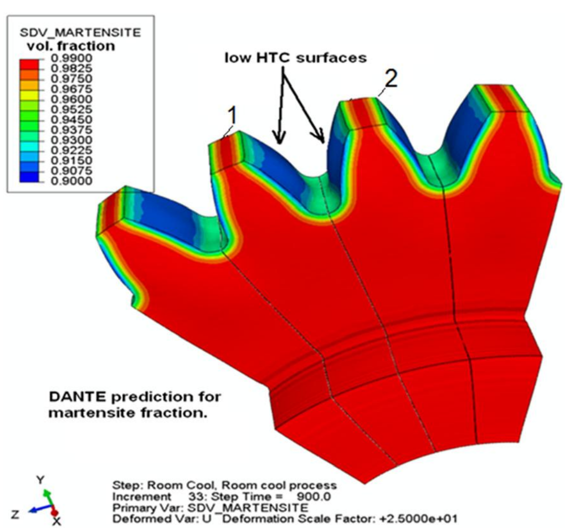

FIG. 10—*The martensite volume fraction in the spur gear in carburized and non-carburized areas after batch quenching. The local film boiling takes place between tooth 1 and tooth 2.*

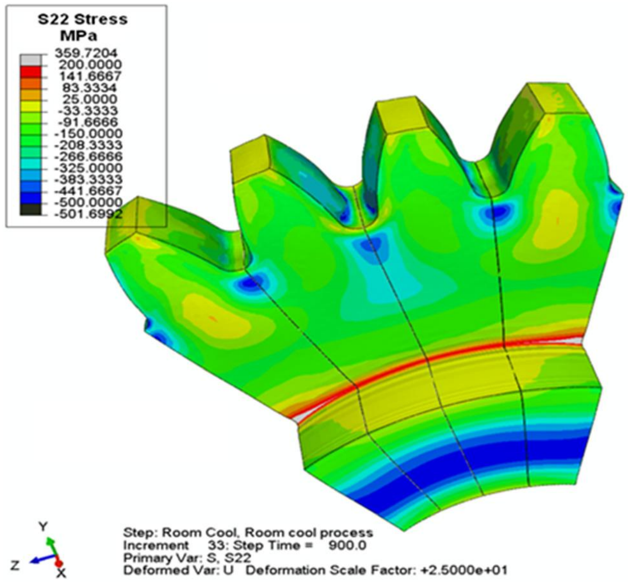

FIG. 11—*Distribution of S22 stress in spur gear after batch quenching.*

Special attention should be paid to designing and manufacturing of IQ equipment that minimizes or completely eliminates local film boiling.

Discussion

As a rule, when performing computer simulation, investigators do not pay attention to local film boiling and take into account only the value of HTC or heat flux, which are characteristics of cooling intensity of the process. Nobody paid serious attention to local film boiling because it is

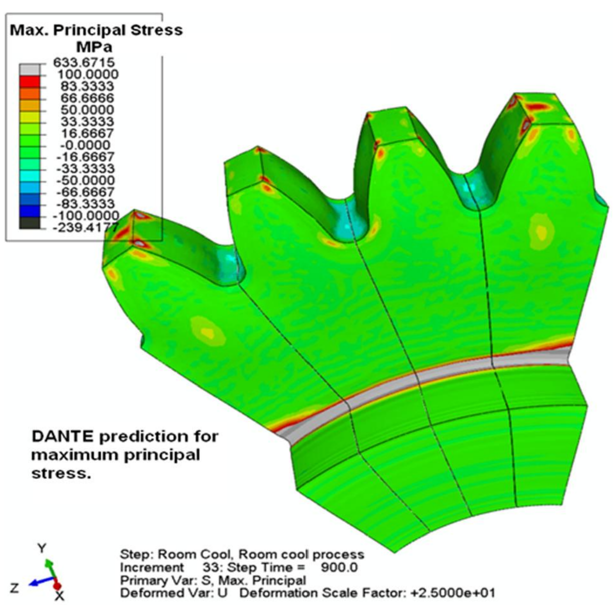

FIG. 12—*Distribution of max principal stresses in spur gear after batch quenching.*

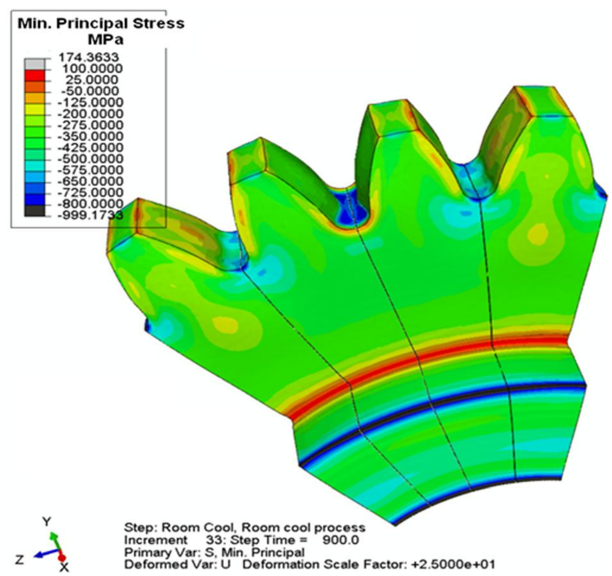

FIG. 13—*Distribution of minimum principal stresses in spur gear after batch quenching.*

connected with critical heat flux densities, which are unknown. At the same time, local film boiling generates large distortions because there are big differences between HTCs on the boundary line of local film boiling–transient nucleate boiling process. As known, HTCs can differ by an order of 10. The transient nucleate boiling process provides immediate martensite transformation and local film boiling delays martensite transformation. As a result, on the boundary line of local film boiling–nucleate boiling big distortions occur due to larger specific volume of martensite (4%). From the computer simulation it follows that distortion is minimum when local film boiling is absent. One can find new ways of decreasing distortion of gears and different kinds of steel parts in

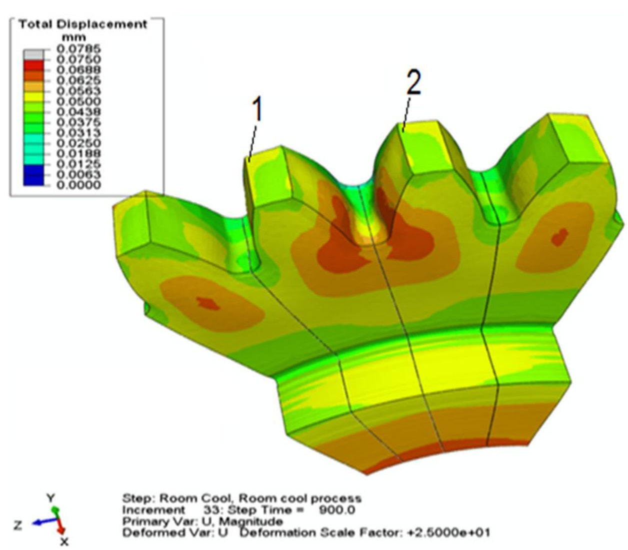

FIG. 14—*Total displacement between tooth 1 and tooth 2 where film boiling took place.*

TABLE 3—*Time required for the surface of steel spheres of different sizes to cool to different temperatures when quenched from 875°C (1,605°F) in 5 % NaOH-water solution at 20°C and moving at 3 ft/s (0.914 m/s), according to French [7].*

	Time, s							
Diameter, mm	700°C	600°C	500°C	400°C	300°C	250°C	200°C	150°C
6.35	0.025	0.030	0.033	0.040	0.06	0.10	0.21	1.05
	0.025	0.040	0.050	0.063	0.12	0.23	0.42	0.67
	0.030	0.040	0.043	0.050	0.09	0.13	0.23	0.36
	0.027	0.037	0.043	0.051	0.09	0.15	0.29	0.69
12.7	0.033	0.040	0.050	0.053	0.07	0.11	0.15	0.43
	0.035	0.038	0.046	0.060	0.09	0.13	0.22	0.49
	0.032	0.050	0.073	0.090	0.11	0.14	0.32	0.92
	0.016	0.043	0.050	0.083	0.17	0.24	0.35	0.65
	0.020	0.040	0.060	0.077	0.10	0.15	0.26	0.53
	0.028	0.042	0.058	0.071	0.11	0.15	0.26	0.60
25.4	0.035	0.040	0.045	0.060	0.08	0.10	0.15	0.40
	0.050	0.050	0.080	0.083	0.11	0.19	0.40	1.20
	0.028	0.040	0.045	0.064	0.14	0.21	0.34	0.71
	0.020	0.020	0.050	0.086	0.19	0.32	0.32	0.99
	0.033	0.042	0.055	0.074	0.13	0.21	0.35	0.82

general from the results of the computer simulation. When performing intensive quenching, three methods should be taken into account:

1. Use small amounts of additives, which destroy completely local film boiling.
2. Use an optimal concentration of water-salt solution, which provides maximal critical heat flux density.
3. Increase the boiling point of a liquid to delay martensite transformation during nucleate boiling process.

These measures could decrease distortion of steel parts during batch quenching.

According to the IQ-2 process, full film boiling and local film boiling should be absent completely. In this case surface temperature of a steel part drops very rapidly to the boiling point of liquid quenchant, slightly exceeding it, and maintains at this level for a rather long time [7,8].

French discovered that surface temperature within the austenitizing temperature and boiling point for different sizes of probes is almost the same (see Table 3).

Kobasko [3] established that surface temperature during quenching of steels can be adjusted by pressure or concentration of salts, which increase the boiling point of liquid (see Fig. 15).

This means that the transformation from austenite to martensite during nucleate boiling process can be delayed, especially when quenching high carbon steels.

From Fig. 6, Fig. 7, and Fig. 15 it follows that during quenching of carburized steel parts martensite transformation begins in the inner layers first, where content of carbon is low and martensite start temperature is high. This situation can change the residual stress distribution in quenched steel parts. In order to take this fact into account, real heat transfer coefficients should be used during computer simulations [7,8]. At present time, a global database is being developed that takes into account effective heat transfer coefficients (HTC) and real HTC. Effective HTC generate less quenching distortion. In spite of that, it is shown that local film boiling is a major disaster for distortion after batch quenching.

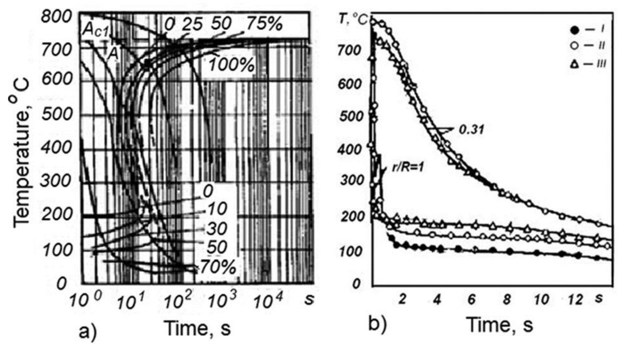

FIG. 15—*CCT diagram for AISI W1 steel (a) and adjustment of surface temperature of a cylindrical specimen 20 mm in diameter made of stainless steel (AISI 304) by changing pressure (b) [2]. i is normal pressue 0.1 MPa; ii is pressure 0.4 MPa; iii is pressure 0.7 MPa.*

The real HTC depends on the overheat of a boundary layer, $\Delta T = T_{Sf} - T_S$ and does not depend on the underheat, $\Delta T = T_{Sf} - T_m$. The point is that the formation of nucleating centers depends on overheating of a boundary layer determined by the equation

$$R_{cr} \cong \frac{2\sigma T_S}{r^* \rho'' \Delta T}, \tag{5}$$

where:

R_{cr} is a critical size of a bubble that can grow and function,
σ is surface tension (N/m),
T_S is saturation temperature (K),
r^* is latent heat of vapor formation (J/kg),
ρ'' is vapor density (kg/m^3), and
$\Delta T = T_{Sf} - T_S$.

Active nucleating centers are the basic carriers of heat that remove heat from a surface and transfer it to a cold bath.

The effective HTC is evaluated as

$$h = \frac{q}{T_{sf} - T_m} \tag{6}$$

and real HTC as

$$h = \frac{q}{T_{sf} - T_S}. \tag{7}$$

The real HTC could be up to ten times larger as compared with the effective HTC. Historically, the effective HTC are widely used in the heat treating industry for recipe development. It has been shown by Kobasko [7,8] that effective HTC can be used successfully for cooling time and cooling rate evaluation at the core of steel parts. During computer simulation the effective HTC generates less distortion due to less gradient of the temperature at the surface of steel parts during quenching. The next step in our investigation is a more precise calculation of gear distortion by using real and effective HTC [8–10].

Summary

1. Local film boiling occurs when $q_{in} \approx q_{cr1}$ and it is the reason for significant distortion of steel parts, especially during batch quenching with many steel parts loaded.
2. The double distortion during quenching is observed when local film boiling takes place between two teeth. The left-hand tooth moves to the right and the right-hand tooth moves to the left.
3. There is a need to develop special additives that can increase the first critical heat flux density to eliminate local film boiling.
4. In the paper the role of local film boiling on changing the displacement of teeth on a spur gear is shown. It is established that significant distortion of gear teeth takes place where local film boiling exists.
5. For computer simulation average HTC were used (for local film boiling 800 $Wm^{-2}K^{-1}$ and for nucleate boiling process effective HTC 25|000 $Wm^{-2}K^{-1}$). When using real HTC, distortion of gears could be even greater.
6. A database for cooling capacity of quenchants is needed, which will help engineers to minimize distortion of steel parts during quenching.

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