Simulation Quenching And Tempering Processes Of a Ring Gear
Rául Lesso-Arroyo and Pablo Orozco-Orozco, Ramón Rodríguez-Castro
Mechanical Engineering Department
Instituto Tecnológico de Celaya
Celaya, Guanajuato, México
Fernando Balderas-López
SSC Group
San Miguel de Allende, Guanajuato, México

Abstract
This paper presents the simulation of heat transfer during quenching and tempering processes in a ring gear of large dimensions. The ring gear is used in the transmission of power to the rollers of a sugar cane mill. Simulation of the thermal processes is necessary to assess the possibility of increasing the useful life of the gear, since this works in very extreme conditions. By achieving an increase in the useful life of the ring gear, considerable savings in production costs for these elements are obtained.

Introduction
This paper presents the simulation of the heat transfer processes of tempering and annealing processes in a ring gear of large dimensions, which is used in the transmission of power to the rollers of a sugar cane mill. A sugar cane mill facility consists of electric turbines, electric motors, a transmission with gears, and milling rolls. In this facility sap is extracted from the sugar cane by a milling process (see Figure 1). The component under analysis is the ring gear shown in Figure 2. After manufacturing of the ring gear, additional heat treatment processes are required to improve mechanical properties (strength, surface hardness) of the gear teeth. These heat treatment processes are tempering and annealing. Better mechanical properties increase the life span of the gear.
A non-uniform working stress is developed in the ring gear during service. The sugar cane, with no previous cleaning, is introduced into the milling rolls along with foreign objects of significant size. These objects produce a non-homogeneous distribution of forces in the milling rolls, which also lead to unequal forces into the transmission. Under this loading condition, the teeth of the gears are subjected to extreme levels of contact stresses in addition to high friction. Consequently, failure of the gear teeth is often present originating recurrent delays in the milling process and thus affecting the sugar production.

The ring gears used for power transmission in the Mexican sugar cane milling facilities have the following geometric and material features:

<table>
<thead>
<tr>
<th>Diameter</th>
<th>1.5 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working section of the gear tooth</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Total weight</td>
<td>2600 Kg</td>
</tr>
<tr>
<td>Rotational speed</td>
<td>6-8 rpm</td>
</tr>
<tr>
<td>Average transmitted power</td>
<td>400-800 HP</td>
</tr>
<tr>
<td>Material</td>
<td>AISI 8620 y 8630</td>
</tr>
</tbody>
</table>

The ring gear must meet some requirements from processing point of view. During solidification, the gear must not develop hot tearing. After initial quenching, hardness should be at least 250 HB. Also, the steel gear must be tough enough to resist the impact loading generated during the milling process. Finally, the steel has to be able to strain harden to reach a hardness in the range of 450-550 HB. The geometry of the ring gear is shown in Figure 3. From this geometry, a solid 3D finite element model is obtained and it will be used to analyze the tempering and annealing processes.
Procedure
Steels containing more than 0.3 wt% C display hot cracking during the solidification process. Thus, the toughness decreases seriously and, if the ring gear is made of this kind of steel, the integrity of the element is under risk. Hot cracking occurs due to segregation that is present during solidification of the melt. During cooling, there exists concentration gradients in the solid and liquid phases of the metal, that is, there is a non-homogeneous distribution of the carbon or carbide phase (cementite).

Changes of state from liquid to solid produce a decrease in volume (shrinking) and thus internal stresses are generated. These internal stresses produce small cracks in the brittle regions of high concentration of carbides. The small flaws are deleterious to the gear material. This phenomenon is more notorious in elements of great size due to the fact that the dimensional changes are substantial and thus the distribution of the alloying elements is not homogeneous throughout the ring gear. It is important to keep in mind that the formation of martensite during quenching depends not only on the carbon contents but also depends on the presence of the alloying elements, the shape of the cross section and volume of the element, etc.

Additions of Boron will be considered in this particular case. Boron greatly improves hardenability in steels and in this way the required carbon concentration decreases, which is beneficent as mentioned above. Therefore, a steel alloy was chosen with less than 0.3 wt% C.

Heat Transfer Process
In order to get the desired mechanical properties two heat treatments are required. These processes are quenching and tempering. Quenching will allow the ring gear to obtain a martensitic microstructure as a result of heating it to the austenitizing temperature and then rapidly cooled with a rate such that just miss the nose of the continuous cooling transformation diagram. In this way austenite will transform into martensite without any pearlite formation. In the as-quenched state, martensite, in addition to being very hard, is extremely brittle; also, any internal stresses that may have been introduced during quenching have a weakening effect. The ductility and toughness of martensite may be enhanced and these internal stresses relieved by a tempering heat treatment. Tempering is accomplished by heating the martensitic steel gear to a temperature below the eutectoid temperature for a specified time period.
**Quenching Process**

The resulting microstructure and the associated mechanical properties depend on the true cooling rate obtained during the quenching process. The larger the difference between the theoretical and the true cooling rates the softer and weaker the transformation products become. In the cooling curve of Figure 4, three cooling stages can be identified. The first one consists of cooling by means of a vapor layer. The second stage is cooling by vapor transport, and the last stage comprises cooling by means of liquid. The latter stage begins when the surface temperature of the component reaches the boiling point of the quenching medium and the cooling rate during this stage becomes lower.

![Figure 4 - Cooling Curve](image)

A convection heat transfer process occurs between a solid medium and a fluid. Convection is the process of transfer of thermal energy by the combined action of heat conduction, energy absorption, and mass movement. The rate of convection heat transfer between the surface of a component and a fluid can be calculated from [1],

\[ q_c = h_c A \Delta T \]

\[ \Delta T = T_s - T_\infty \]  \hspace{1cm} (1)

where
- \( q_c \) = Convective heat flux
- \( A \) = Heat transfer area
- \( T_\infty \) = Free flow temperature
- \( T_s \) = Surface temperature
- \( h_c \) = Average convective coefficient

In this particular case the fluid used is quenching oil and the solid material is the above mentioned alloy steel AISI 8620 which has the following thermophysical properties:

<table>
<thead>
<tr>
<th>Temperature T(°K)</th>
<th>Density ( \rho )(Kg/m(^3))</th>
<th>Viscosity ( \mu )(g/ms)</th>
<th>Thermal Conductivity ( K )(W/m(^°)K)</th>
<th>Specific Heat ( C_p )(KJ/Kg(^°)K)</th>
<th>Prandt No.</th>
<th>Kinematic Viscosity ( \nu )(m(^2)/s) x 10(^-)</th>
<th>Thermal Diffusivity ( \alpha )(cm(^2)/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>561</td>
<td>716</td>
<td>2.94</td>
<td>0.114222</td>
<td>2.825</td>
<td>72.6</td>
<td>4.10</td>
</tr>
<tr>
<td>Steel 8620</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>273</td>
<td>7.83</td>
<td></td>
<td></td>
<td></td>
<td>55</td>
<td></td>
<td></td>
</tr>
<tr>
<td>373</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>673</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>42</td>
<td></td>
<td></td>
</tr>
<tr>
<td>873</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1273</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>29</td>
<td></td>
<td>0.148</td>
</tr>
</tbody>
</table>
In order to calculate the convection heat transfer coefficient, the operating conditions were taking into account. In these conditions the initial and final temperatures of the component are set to 900 °C and 150 °C, respectively, whereas the working temperature of the oil is set to 50 °C. The film temperature $T_f$ is calculated as, [4]

$$T_f = \frac{T_s + T_\infty}{2}. \quad (2)$$

A higher heat transfer is attained for turbulent flow. Then the Reynolds number in transition to turbulent gives the velocity. This Reynolds number is $Re=5\times10^5$, where

$$Re = \frac{\rho U_\infty L}{\mu} = \frac{U_\infty L}{v}, \quad (3)$$

and

$U_\infty$ = Velocity of quenching fluid,  
$L$ = length.

Once the fluid characteristics are known, the velocity of fluid is calculated to make sure that turbulent flow is a major event.  
On the other side, the outer circumference of the gear will be considered as a cylinder and the faces of the gear as flat plates. Therefore, the convective heat transfer coefficient in each surface can be estimated by using appropriated relations. In the case of flat plates, the following relation was used [4],

$$N_{U_\ell} = 0.037 \Pr^{\frac{1}{2}} \left\{ \Re^{\frac{1}{2}} - 23550 \right\}, \quad 0.6 < \Pr < 60, \quad (4)$$

and the convective heat transfer coefficient $h_1$ is calculated from

$$N_{U_\ell} = \frac{h_1 L}{k} \quad (5)$$

On the other hand, for the cylindrical surface the following was used [4],

$$N_{U_d} = 0.3 + \left[ \frac{0.62 \Pr^{\frac{1}{2}} \Re D^{\frac{1}{2}}}{1 + \left\{ \frac{0.4 \Pr}{282000} \right\}^{\frac{1}{9}}} \right] \left[ 1 + \left\{ \frac{\Re}{282000} \right\}^{\frac{1}{9}} \right]^{\frac{9}{16}}, \quad \Pr > 0.2, \quad (6)$$

where the convective heat transfer coefficient $h_2$ is obtained from

$$N_{U_r} = \frac{h_2 D}{k}. \quad (7)$$
Finally, upon substituting values of Re, Pr, D, K, U∞, etc., the calculated values of \( h_1 \) and \( h_2 \) are 193.57 and 315.86 W/m\(^2\)°K, respectively.

**Tempering Process**

After the quenching process, the component has a highly brittle martensitic structure and, in addition, has a high level of internal residual stresses. Therefore, the quenching process is followed by a tempering heat treatment. Tempering improves ductility and toughness, and relieves internal stresses. There is a dependence of mechanical properties on tempering temperature. At higher tempering temperature ductility and toughness increase, whereas strength and hardness decrease.

The conditions used in the analysis for the tempering process are the following: A heat treatment furnace with eight burners of 300,000 BTU/hr each, giving a total heat power of \( q = 703.2 \) KW. The flame temperature was obtained from [2],

\[
\Delta H^°_{298} + \sum_{298}^{T_F} mC_{p,\text{prod}} dT = 0, \quad T_F = 3275°K. \quad (8)
\]

The total area of heat transfer is 4.616 m\(^2\), and the convective heat transfer coefficient utilized during heating is \( h = 53.43 \) W/m\(^2\)°K for the eight burners which was calculated from

\[
q = h A_S (T_F - T_∞), \quad (9)
\]

where,
- \( A_S \) = Surface area
- \( T_F \) = Flame temperature
- \( T_∞ \) = Medium temperature

**Preprocessing**

In the preprocessing stage the 3D model was imported in step format of Mechanical Desktop, see Figure 5. An important simplification was the rotational symmetry of the geometry and loading. Thus, only a quarter of the model was analyzed and this is shown in Figure 6. The ANSYS program generated a mapped mesh with 20496 nodes and 18102 elements. Figure 7 illustrates the finite element model of the ring gear. The 3D solid geometric finite element chosen was the thermal element SOLID70, see Figure 8. This element has 8 nodes with a single degree of freedom per node, temperature. By using this kind of element along with a relatively high-density mesh, a good approximation is obtained despite the fact that the solid70 is a linear element. Furthermore, it can be used in transient and steady state analyses with compatibility in conduction and convection.
Figure 5 - Import Gear(230,38),(668,322)

(230,339),(668,513)

Figure 6 - Symmetric Model

Figure 7 - Finite Element Model
Another important aspect in this stage was the application of the thermophysical properties of the material and of the quenching oil. In this case tables of properties were defined as a function of temperature. Thermal conductivity as a function of temperature for the AISI 8620 steel is shown in Figure 9.
Solution

In the solution stage temperature and convection boundary conditions were applied for the quenching and tempering processes. This was done on the plane flat faces and on the faces of the gear teeth. Figure 10 presents the specific boundary conditions for each heat treatment. Finally, a transient analysis was run using the PCG solution method, considering 120 minutes immersion in quenching oil with 120 loading substeps for the quenching process. Then, for the tempering heat treatment, 40 minutes were considered as the cooling period with 40 loading substeps in order to get a better cooling curve.

![Figure 10 - Thermal Boundary Conditions](image)

Postprocessing

In this case some figures and plots are presented which show the temperature distribution in the finite element model for each case under study, as well as the cooling curves as a function of time during quenching and tempering.

**Quenching Process**

Figure 11 shows that after the gear was immersed for two minutes (120 s) in the quenching fluid, a very low temperature gradient is present. Therefore, there is no possibility of thermal shock when the gear is introduced into the quenching pool due to uniform cooling. As the time goes on (1114 s), the gradients of temperature are kept low and cooling is uniform throughout the element, see Figure 12. As can be seen from figures 13, 14, 15, 16, 17, 18, and 19, the zones with a higher cooling rate are the external corners of the gear teeth. In these zones the heat dissipation is better because the fluid is interacting with the teeth from different directions, which does not occur in other zones such as in the flat faces of the gear. Finally, Figures 20 and 21 presents cooling rates for three points in the ring gear. Although the whole gear does not attain a uniform temperature of 150 °C, the outer part and the teeth reach that temperature. Thus, the teeth are effectively hardened while the inner part of the gear gets a softer structure.
Figure 11 - Distributions of Temperatures, 2 min.

Figure 12 - Distributions of Temperatures, 4 min.
Figure 13 - Distributions of Temperatures, 10.5 min.

Figure 14 - Distributions of Temperatures, 13.25 min.
Figure 15 - Distributions of Temperatures, 18.5 min.

Figure 16 - Distributions of Temperatures, 24.5 min.
Figure 17 - Distributions of Temperatures, 34.5 min.

Figure 18 - Distributions of Temperatures, 40 min.
Figure 19 - Distributions of Temperatures, 40 min(cut).

Figure 20 - Three Points Analyzed
Tempering Process

The tempering analysis begins with the application of the final quenching temperature, 150 °C, as can be observed in Figure 22. In addition, the tempering boundary conditions where applied, that is, 650°C tempering temperature for a period of time of 40 minutes under the heating conditions of the furnace, see figures 23, 24, 25, 26, 27 and 28. It is important to mention that the effects of radiation heating inside the furnace where neglected during the analysis, and this can suggest that the tempering heating time could diminish. However, with an extra time it can be sure that the whole element achieves the temperature of 650 °C.
Figure 22 - The Final Quenching Temperature

Figure 23 - The Final Quenching Temperature, 650 °C, 100 Sec.
Figure 24 - The Final Quenching Temperature, 650 °C, 287.3 Sec.

Figure 25 - The Final Quenching Temperature, 650 °C, 587.3 Sec.
Figure 26 - The Final Quenching Temperature, 650 °C, 787.3 Sec.

Figure 27 - The Final Quenching Temperature, 650 °C, 1000 Sec.
### Conclusion

It is important to point out that, according to the results of the numerical analysis developed, zones with notable differences in temperature were not found, especially zones with a complex geometry (teeth) because this could reduce the affectivity of tempering. The required volume of quenching oil will be diminished if its re-circulation is considered. The minimum velocity of the fluid has to be taken into account (> 1.4 m/s) in order to get a turbulent flow and thus maximize the heat transfer.

For numerical experimentation purposes the temperature of the quenching medium was taken as a constant. In spite of this, the experimentation provided important clues, such as the period of time of the quenching process that was between 30 and 40 minutes, and the tempering time that was approximately 6.5 hours. With these results optimization of costs and time can be possible.

### References