Finite element analysis of quenching process to optimize cooling strategy of spur gear

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Abstract—Quenching control continues to be of great concern to the metals processing industry since it exhibit tremendous effects on quality and profitability. This paper presents the simulation of heat transfer during quenching and tempering processes in a spur gear of small dimensions. The spur 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 spur gear, considerable savings in production costs for these elements are obtained.

Keywords-spur gear; quenching media; tempering; time stepping; optimum cooling points

I. INTRODUCTION

This paper presents the simulation of the heat transfer processes of tempering and annealing processes in a spur gear of small 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 spur gear shown in Figure 2. After manufacturing of the spur 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.
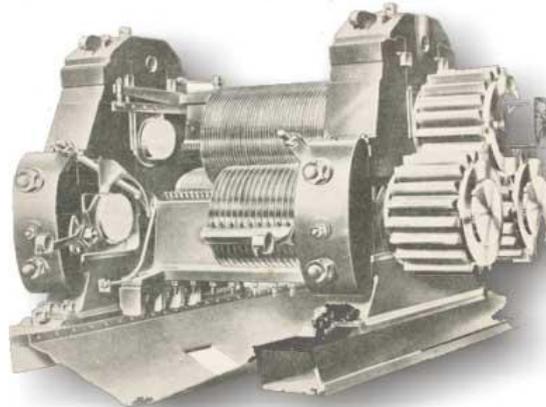
Figure 1. Sugar cane mill facility

A non-uniform working stress is developed in the spur 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.
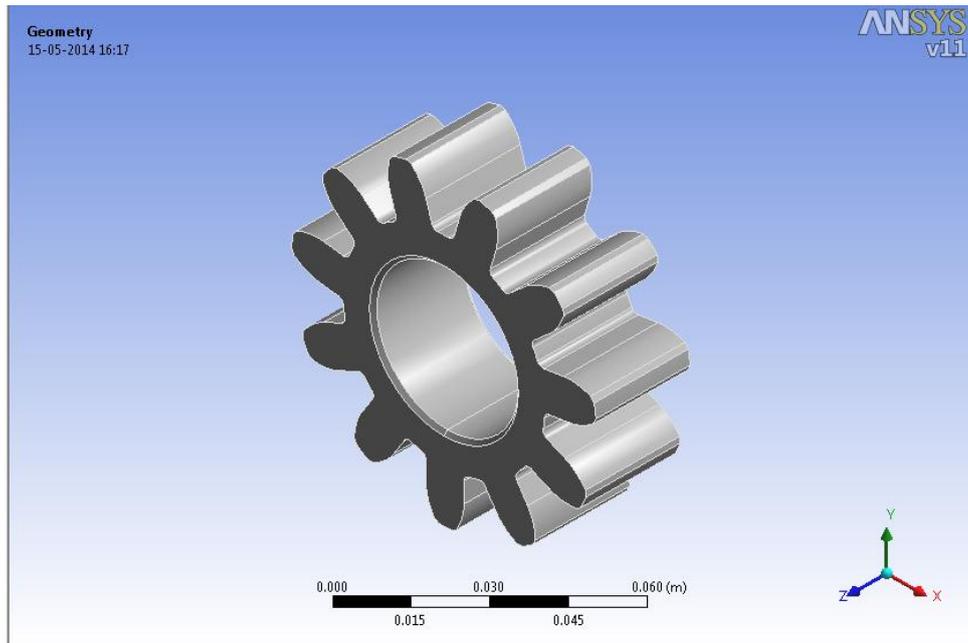
Figure 2. Spur gear

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

Table 1. Geometric & Material properties

Diameter	82.55 mm
Working section of the gear tooth	25.40 mm
Total weight	0.5243 kg
Average transmitted power	1 HP
Material	Structural steel

II. 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 3, 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.
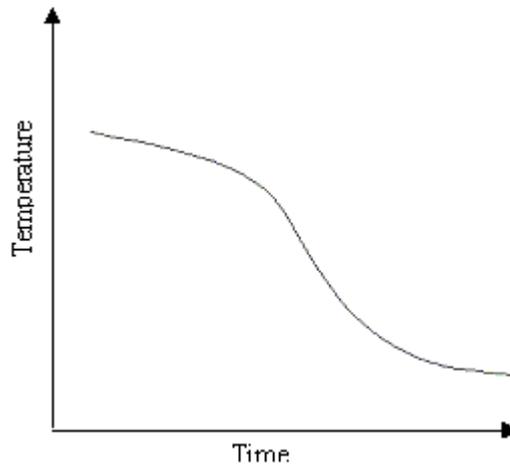
Figure 3. Cooling curve

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],

$$q_c = h_c A \Delta T$$
$$\Delta T = T_s - T_\infty$$

Where

q_c = Convective heat flux
A = Heat transfer area
T_∞ = Free flow temperature
T_s = Surface temperature
h_c = Average convective coefficient

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 950 °C and 150 °C, respectively, whereas the working temperature of the oil is set to 45 °C. The film temperature T_f is calculated as [4],

$$T_f = \frac{T_s + T_\infty}{2}$$

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=5x10^5, where

$$\text{Re} = \frac{\rho U_\infty L}{\mu} = \frac{U_\infty L}{\upsilon}$$

where

U_∞ = 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],

$$N_{U_L} = 0.037 \, Pr^{1/3} \left\{ Re^{4/5} - 23550 \right\}, \qquad 0.6 < Pr < 60,$$

And the convective heat transfer coefficient his calculated from

$$N_{U_L} = \frac{h_1 L}{k}$$

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

$$N_{U_D} = 0.3 + \left[\left\{ \frac{0.62 \, Pr^{1/3} \, Re \, D^{1/2}}{\left(1 + \left\{ \frac{0.4}{Pr} \right\}^{2/3} \right)^{1/4}} \right\} \left\{ 1 + \left(\frac{Re}{282000} \right)^{5/8} \right\}^{4/5} \right], \qquad Pr > 0.2,$$

Where the convective heat transfer coefficient h_2 is obtained from

$$N_U = \frac{h_2 D}{k}$$

Finally, upon substituting values of Re, Pr, D, K, U_∞, etc., the calculated values of h_1 and h_2 are 153.57 and 171.86 W/m^2 °K, respectively

III.   PRE PROCESSING

In the preprocessing stage the 3D model was imported in step format of Mechanical Desktop. An important simplification was the rotational symmetry of the geometry and loading. The ANSYS program generated a mapped mesh with 10592 nodes and 1896 elements. Figure 4 illustrates the finite element model of the spur gear. By using kind of element along with a relatively high-density mesh, a good approximation is obtained. Furthermore, it can be used in transient and steady state analyses with compatibility in conduction and convection.
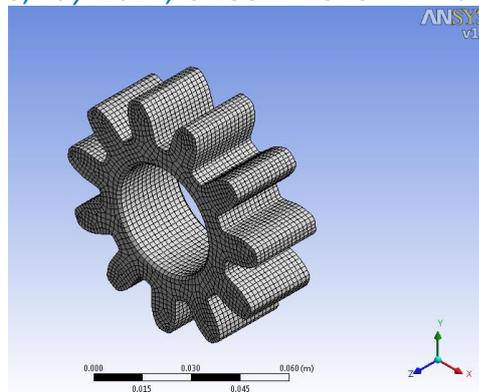
Figure 4. Finite element meshed model

Another important aspect in this stage was the application of the thermo physical properties of the material and of the quenching oil. In this case tables of properties were defined as a function of temperature. Alternating stress for the structural steel is shown in Figure 5.
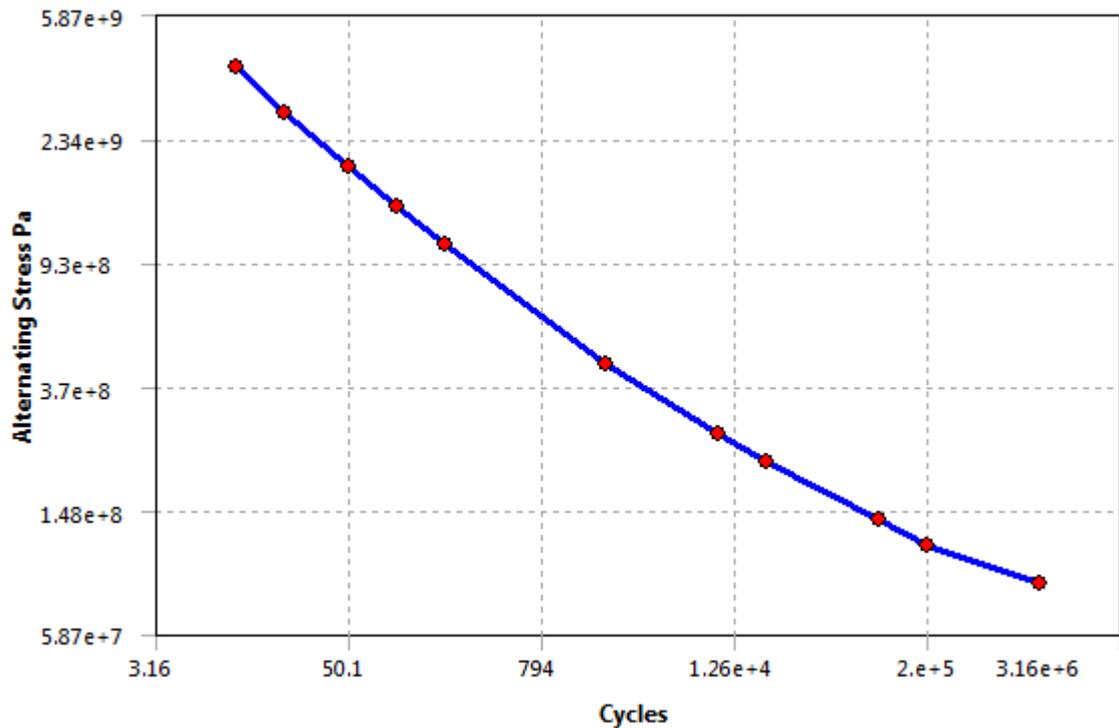
Figure 5. Alternating stresses of structural steel

IV.   SOLUTION

In the solution stage temperature and convection boundary conditions were applied for the quenching process. This was done on the plane flat faces and on the faces of the gear teeth. Figure 6 presents the specific boundary conditions for heat treatment. Finally, a transient analysis was run using the PCG solution method, considering 10 seconds immersion in quenching oil with 10 loading sub steps for the quenching process.
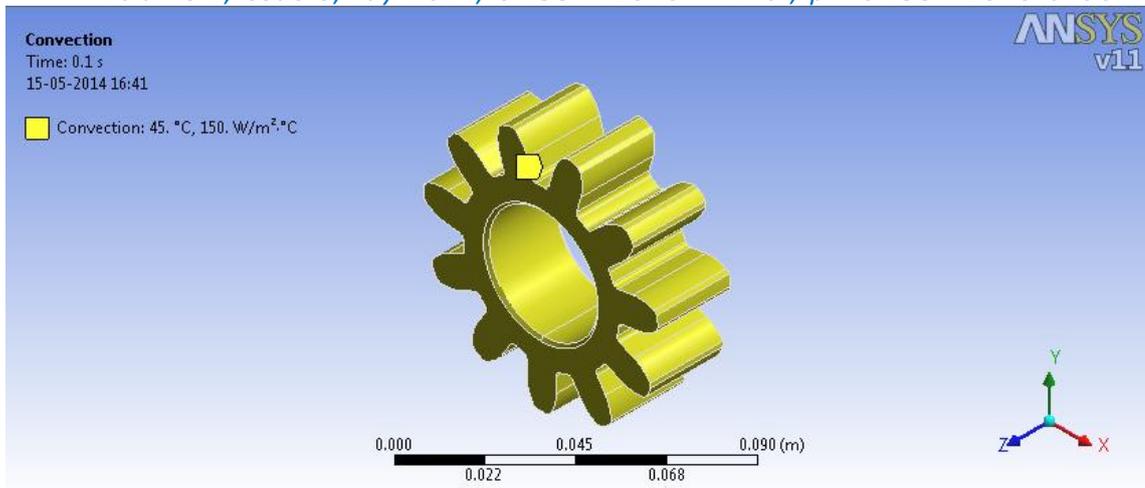
Figure 6. Convection load applied to spur gear

V. POST PROCESSING

Figure 7 shows that after the gear was immersed for 0.1 seconds 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, the gradients of temperature are kept low and cooling is uniform throughout the element, see Figure 8. As can be seen from figures 9, 10, 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.
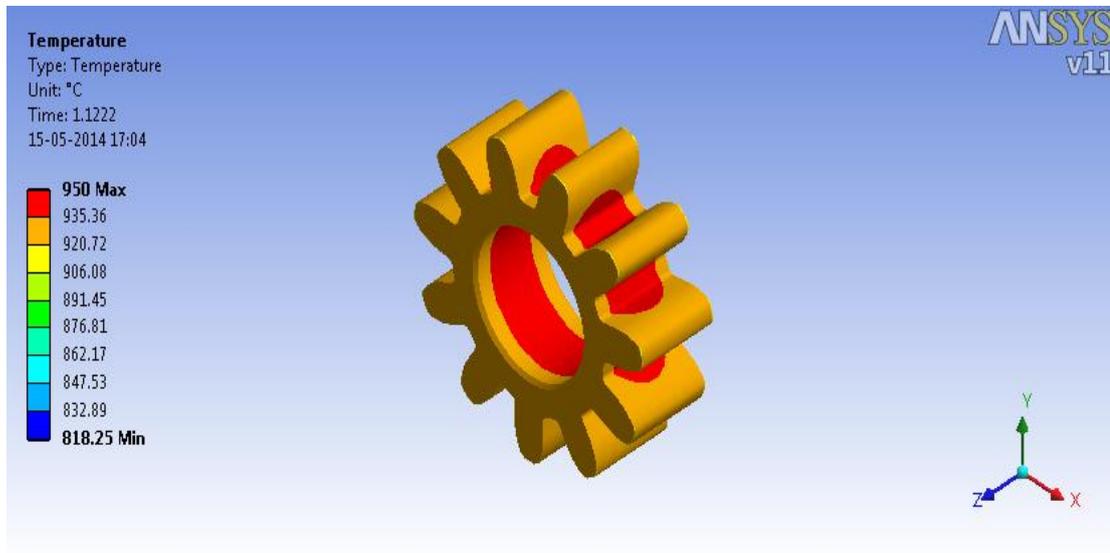
Figure 7. Distribution of temperature, 1.122 s
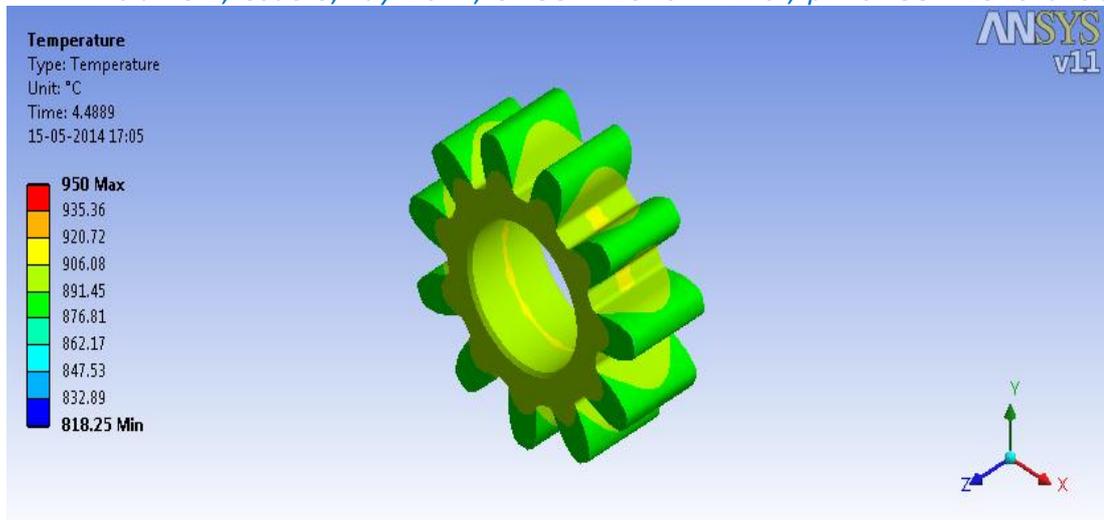
Figure 8. Distribution of temperature, 4.488 s
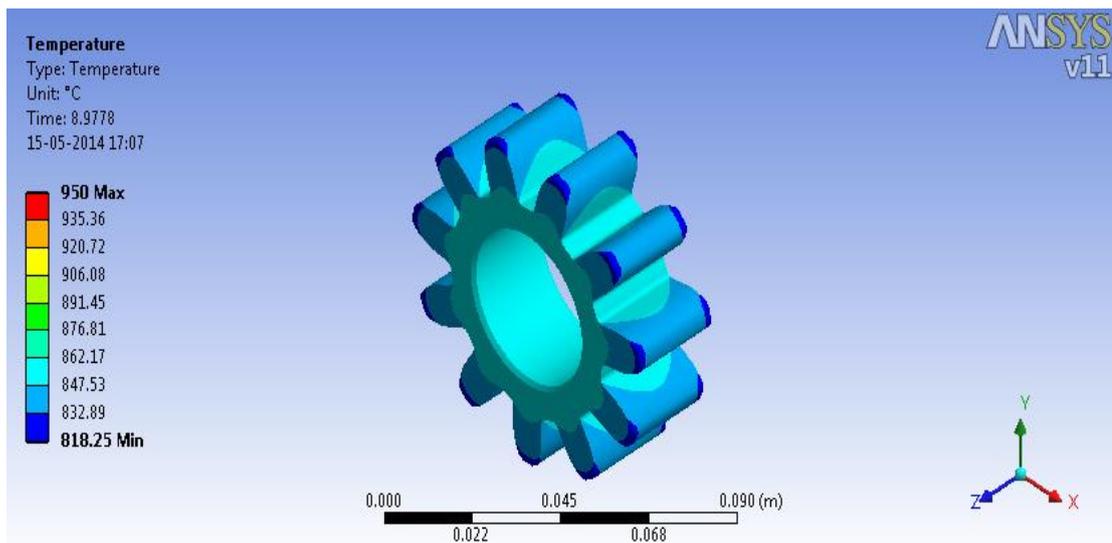
Figure 9. Distribution of temperature, 8.977 s
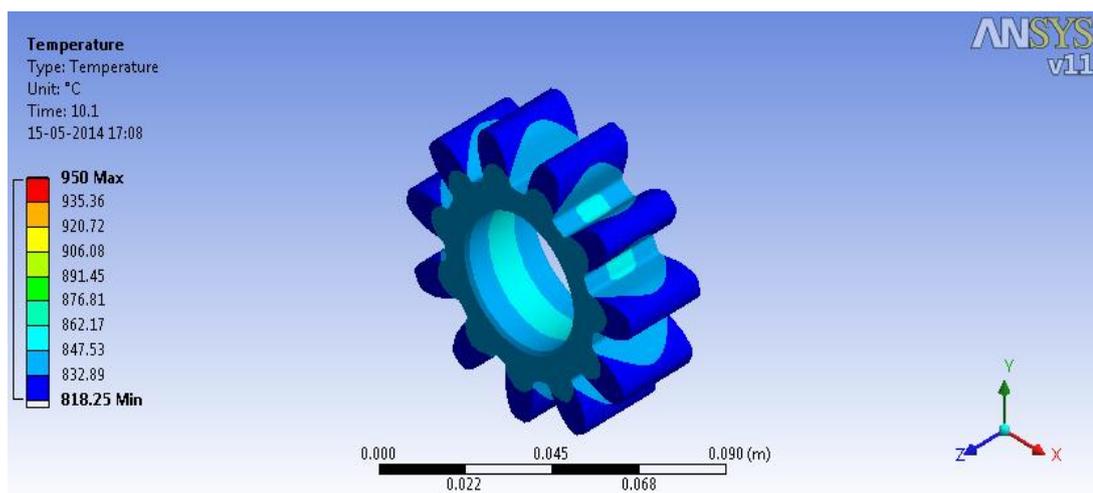
Figure 10. Distribution of temperature, 10.100 s
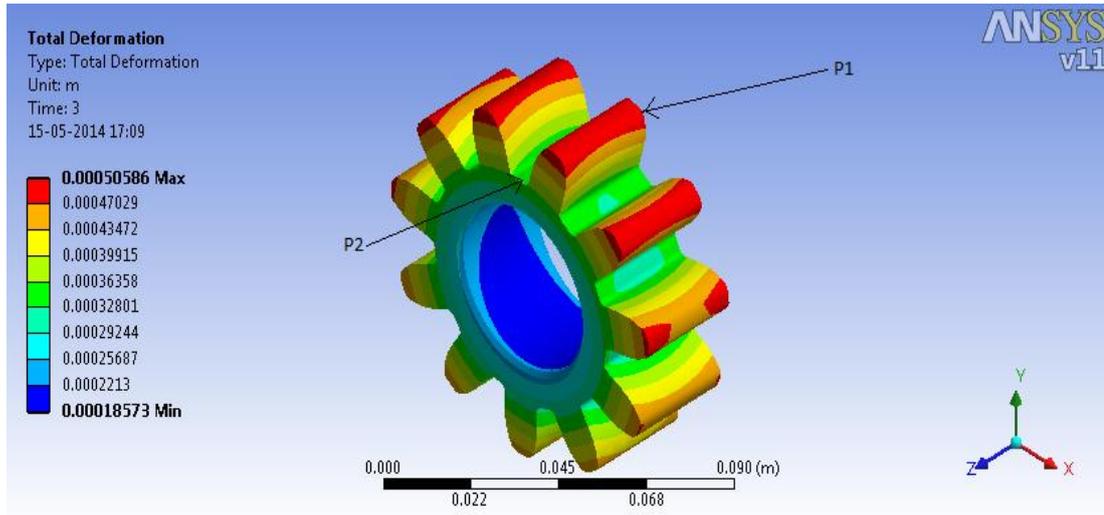
Figure 11. Total deformation of spur gear

VI.   CONCLUSION

It is important to point out that, especially zones with a complex geometry (teeth) 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. It has been found that phase transformation is the main reason for the large distortion. Non-phase changing metals may have distortion when they are intensively quenched.

The optimum cooling strategy can be obtained from finite element simulations. The simulation results show that the distortion and stresses can be reduced with an appropriate cooling strategy. Increasing the cooling at the mass lumped regions reduces only the distortion but increases the stresses. However, an enhanced cooling at the mass-lumped region, and reduced cooling at the edges and thin parts, reduces both distortion and stresses. This optimization procedure is independent of geometries and metals. In practice, the local cooling can be adjusted e.g., with a nozzle field of gas or atomized water sprays.

REFERENCES

[1] Kreith F. , "Principios de transferencia de calo"r, Herrero Hermanos Press, 1986, México.
[2] Ozisik M. R., Heat Transfer: A basic approach, McGraw Hill, 1996, NY, USA.
[3] Avner, S., Introducion a la metalugia fisica, McGraw Hill, 1998,Mexico.
[4] Incropera F.P., De UIT F. P., Fundamentals of heat and mass transfer, John Wiley and Sons, 1996, NY, USA.
[5] Honeycombe R., Badeshia K., Microstructure and Properties, Academic Press, 1972.
[6] ANSYS Inc., Seminar notes of Heat transfer, Ansys Press,1999, PH, USA.
[7] ANSYS Inc., Verification Manual, Ansys Press, 2000, PH, USA