Simulation of Low Pressure Carburizing and Low Pressure Oil Quenching Process using ABAQUS for Finding Distortions in Component

S. P. Wadkar†, Himanshu J. Patil$, Shubham R. Tiwari$

Abstract - In this paper, based on the principles of heat transfer and thermal elastic-plastic theory, the heat treatment process optimization for dog clutch gear is proposed according to the structural characteristics of the gear and material properties of SCM415. To simulate the effect of Low pressure carburizing and Low pressure oil quenching process on tooth deformation and residual stress distribution, a heat treatment analysis model of gear is established, stress and deformation of gear teeth changing with time are analysed. The simulation results show that gear tooth hardness increases, tooth surface residual compressive stress increases and tooth deformation decreases after heat treatment process optimization. It can be beneficial for improving the fatigue strength and performance of gears.

Keywords – Carburizing, Distortions in treatment, Gear, Heat Treatment, Quenching,

I. INTRODUCTION

A. Carburizing

Carburizing is the process of diffusing carbon into steel so that the surface will become harder. Steel is surrounded with some form of graphite then high temperature and pressure added to the system so that the carbon can diffuse into the steel. This method is limited by contact between the steel and the carbon so it often has problems with the continuity of the case depth. Carburizing can also take place in gas atmospheres at or near standard atmospheric pressure. This method is attractive because a vacuum is not required so some processing cost can be reduced. However, the gas interactions do not allow even case depths. While the gas can easily strike exposed areas such as the top-land of a gear tooth the gas has problems distributing enough carbon at the root of the tooth. This happens because the carbon rich gas will initially strike the tooth root and the carbon will diffuse into the steel. In the last several decades vacuum carburizing was created. This occurs by creating a weak vacuum (10-25 Pascal) around the part to be carburized and then a small amount of carbon rich gas is introduced into the atmosphere. This gas increases the pressure to about 80,000 Pascal in vacuum carburizing and 450 to 1700 Pascal for low pressure carburizing (Benitez). The gas will move very rapidly and because physics dictates that atoms and molecules move from areas of high concentration to areas of low concentration the carbon rich gas will be attracted to the carbon deficient steel. When the carbon is on the surface of the steel some will diffuse into the steel. The carbon deficient gas will then be replaced by the carbon rich gas fairly quickly because of the speed the molecules move in the vacuum. This is an efficient process because the vacuum required is relatively low and the composition of the gas can be well controlled. Vacuum carburizing is also beneficial because of the low amount of oxygen in the carburizing atmosphere. One of the problems with processing of steels is the oxidizing of the steel at higher temperatures.

B. Hardening

Hardening is a metallurgical and metalworking process used for increasing the hardness of a metal. The hardness of a metal is directly proportional to the uniaxial yield stress at the location of the imposed strain. A harder metal will have a higher resistance to plastic deformation than a less hard metal. Hardening is performed to:

1) To increase hardness, wear resistance and ability to cut other materials.

2) To improve strength and toughness.

The hardening process consists of heating the hypo-eutectoid steel (%C = 0 to 0.8%) to a temperature 30 to 50 ºC above the Upper Critical temperature. For hypereutectoid steels (%C = 0.8 TO 2.11%) to a temperature 30 to 50 ºC above the Lower Critical temperature.

Holding at this temperature for considerable time, to complete phase transformation and sudden cooling in water or oil. When the component is subjected to hardening process in a quenched medium, the outer surface of the component experiences cooling effect immediately compare to core of the component i.e. outer surface produces small grains (martensite) and whereas core remains with large grains (Austenite Phase) i.e. Outer surface is hard and core remains in soft condition.

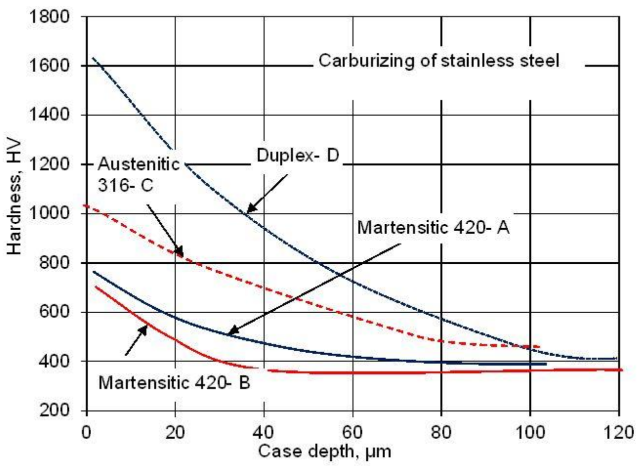

Fig. 1. Phase Transformation vs Hardness

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C. Quenching

In materials science, quenching is the rapid cooling of a workpiece to obtain certain material properties. A type of heat treating, quenching prevents undesired low-temperature processes, such as phase transformations, from occurring. It does this by reducing the window of time during which these undesired reactions are both thermodynamically favourable, and kinetically accessible; For instance, quenching can reduce the crystal grain size of both metallic and plastic materials, increasing their hardness.

In metallurgy, it is most commonly used to harden steel by introducing martensite, in which case the steel must be rapidly cooled through its eutectoid point, the temperature at which austenite becomes unstable. In steel alloyed with metals such as nickel and manganese, the eutectoid temperature becomes much lower, but the kinetic barriers to phase transformation remain the same. This allows quenching to start at a lower temperature, making the process much easier. High speed steel also has added tungsten, which serves to raise kinetic barriers and give the illusion that the material has been cooled more rapidly than it really has. Even cooling such alloys slowly in air has most of the desired effects of quenching. Extremely rapid cooling can prevent the formation of all crystal structure, resulting in amorphous metal or "metallic glass".

C.1 Quenching Process

The process of quenching is a progression, beginning with heating the sample. Most materials are heated from anywhere in between 815 to 900 °C (1,500 to 1,650 °F), with careful attention to temperatures throughout the heating process. Minimizing uneven heating and overheating can be a key to imparting desired material properties.

The second step in the quenching process after heating is soaking. Objects can be soaked in air (air furnace) or liquid bath, or even a vacuum. The recommended time allotment in salt or lead baths is usually 0 to 6 minutes. Soaking time can range a little larger within a vacuum and, soak is generally similar to that in air. Like in the heating step, it is important that the temperature throughout the sample remains as uniform as possible during soaking. Once the soaking is finished, part moves on to the cooling step. During this step, the part is submerged into some kind of quenching fluid; different quenching fluids can have a significant effect on the final characteristics of quenched parts. Water is one of the most efficient quenching media where maximum hardness is desired, but there is a small chance that it may cause distortions and tiny cracks. When hardness can be sacrificed, whale oil, cottonseed oil or mineral oils are often used.

C.1.1 Mathematical Model of Quenching Process

C.1.1.1 Temperature field of quenching process

Transient heat conduction equation in the process of

Carburizing and quenching is,

$$\rho C_p \frac{\partial T}{\partial t} = \lambda\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial x^2}\right) + Q\,,$$

Where T is the instantaneous temperature of object, t is the time of quenching process, λ is the thermal conductivity of the material, ρ is the material density, C_P is the specific heat of material, Q is the heat generated by plastic and potential phase transition, and r is the radial and axial coordinate position of object. Assuming the thermal conductivity of the material is isotropic, T changes with t during the heat treatment. λ, C_P and Q are all the functions of T.

During heat treatment process, the boundary condition of heat transfer, the convective heat transfer between gear and quenching medium, is

$$q = H_k (T_w - T_f)\,,$$

Where q is the heat flux through the boundary, H_k is the heat transfer coefficient between gear and quenching medium, and T_f and T_w are the temperatures of quenching medium and face gear, respectively.

When calculating stress fields in the process of carburizing and quenching, no external load is considered. The stresses and strains are caused by variable temperatures. So the domain belongs to thermal elastic-plastic one.

C.1.1.2 Stress field of quenching process

Stress field in the quenching process:

The strain increment $d\varepsilon_{ij}$ in quenching process is presented as

$$d\varepsilon_{ij} = d\varepsilon_{ij}^{e} + d\varepsilon_{ij}^{p} + d\varepsilon_{ij}^{th} + d\varepsilon_{ij}^{tr}$$

Where $d\varepsilon_{ij}^{e}, d\varepsilon_{ij}^{p}$, $d\varepsilon_{ij}^{th}$, $d\varepsilon_{ij}^{tr}$ of elastic strain, plastic strain, thermal strain and phase transformed strain, respectively.

The increment of phase transformed strain is

$$d\varepsilon_{ij}^{tr} = [\beta^0 + (\alpha_M - \alpha_A)T]dV$$

Where β^0 is the coefficient of volume expansion for martensite at 0°C, and α_M and α_A are the thermal expansion coefficients of martensite and austenite, respectively.

D. Distortion

Power transmission gear manufacturing for critical industrial applications requires an understanding of many factors, including both heat treat process-related variables (pre-treatment, load arrangement, process selection and technique, quench considerations, and equipment design) and the various component-related variables that influence distortion (material chemistry, hardenability, part geometry, design considerations, and steel quality). Of these factors, those resulting from transformation during heating and cooling produce internal stress/strain induced by volumetric changes due to these transformations and result in localized deformations and general part distortions.

When a precision machined gear is placed in a furnace, raised to austenitizing temperature, carburized for an extended time and then quenched to produce a martensitic microstructure, distortions are unavoidable. There are, however, ways to minimize and/or control the amount and type of distortions, making it more predictable from part to part and lot to lot. As a result, machining processes can be developed which will consistently yield gears that meet the design requirements, both dimensionally and metallurgically.

II. HEAT TREATMENT MODEL OF GEAR

To perform finite element analysis of gear heat treatment process following model considered is shown in fig. 2 and 3.

Material Properties:

Name – SCM415

Young's modulus - 206.8 GPa

Poisson's ratio - 0.3

Yield stress - 248.2 MPa for 121°C

Density - 7832 kg/m3

Specific heat - 0.6 kJ/kg °C

Thermal conductivity - 58.8 W/m°C

The film coefficient on the surface of the plate is -193.1 W/m^2°C.

Fig. 2. Isometric View

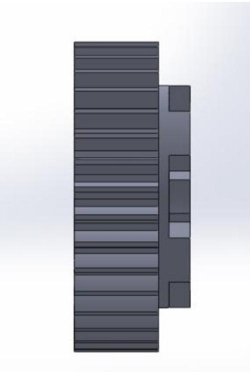

Fig. 3. Side View

III. COMPUTATIONAL SIMULATION

Meshing of Gear: Pure Hexahedral mesh considered for good results

Fig. 3. Mesh Type: Hexahedral, Number of Nodes = 95520, No of Elements = 83080.

A. Carburizing

Table I
Summery for Carburizing

Sr. No	Process	Product/Process Specification Tolerances
1	Temperature	880 ºC ± 10 ºC
2	Time	280 min ± 20 min
3	Burner Ratio	1:40 ± 1:5
4	Furnace Pressure	15 ± 5 mm
5	Probe reference air	0.5 CFH
6	Probe purge air	4 CFH
7	Roof fan RPM	500-600
8	Dew Point	(-1 to -3 ºC)
9	Endo gas flow	600 ± 50 CFH

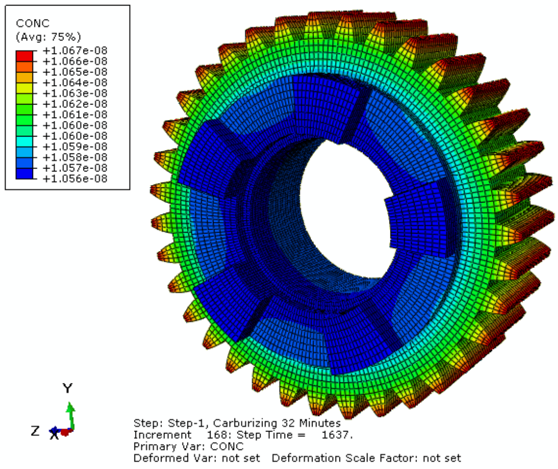

Fig. 4. Carbon Concentration Results of 3D Vacuum Carburizing Simulation

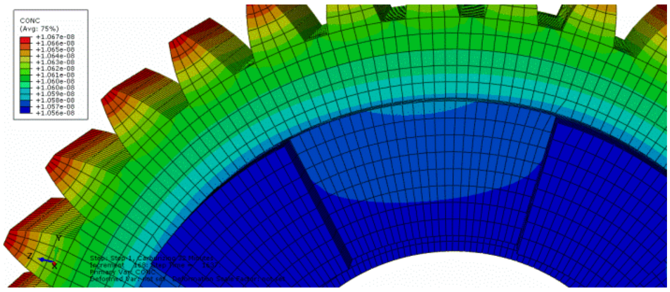

Fig. 5. Close up-Carbon Concentration Results of 3D Vacuum Carburizing Simulation

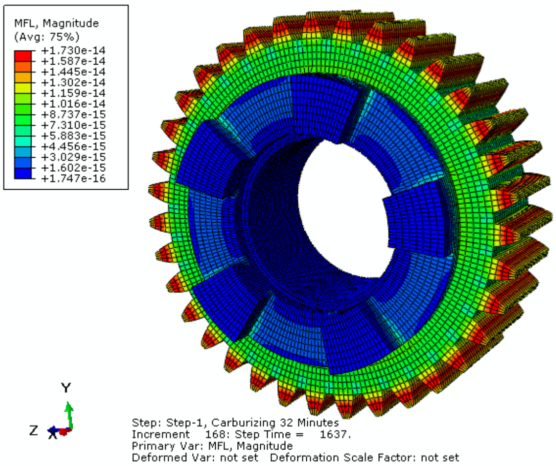

Fig. 6. MFL (Magnitude and components of the concentration flux vector)

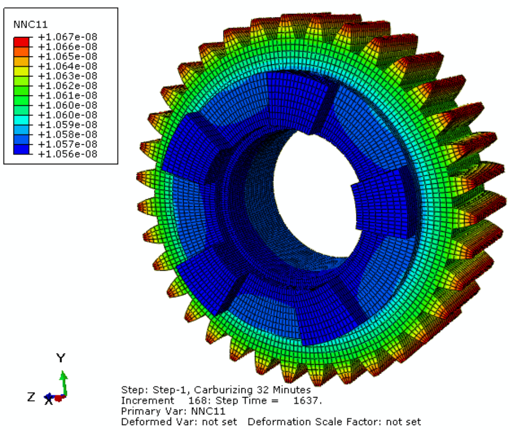

Fig. 7. Normalized Concentration

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B. Quenching

B.1 Thermal Transient Analysis

Table II
Summery for Quenching

Summery for Quenching		
Sr. No	Process	Product/Process Specification Tolerances
1	Hardening End Temperature	840 ºC ± 10 ºC
2	Temperature	120 ºC ± 10 ºC
3	Time (Dip)	3 min ± 1 min
4	Time (Drain)	3 min ± 1 min
5	Oil level	Within green band
6	Agitation	RPM (500-600)

B.1.1 Temperature Contours by Quenching Analysis

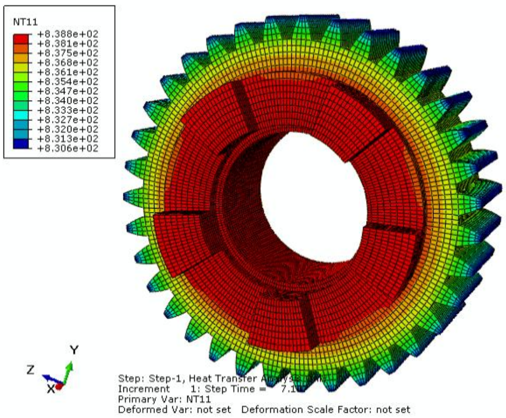

Fig. 8. At Time - 7 sec, Temperature - 830

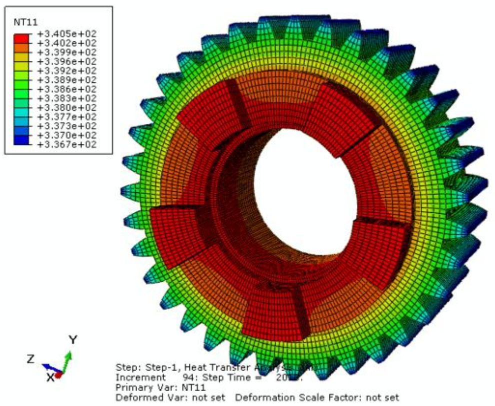

Fig. 9. At Time - 2000 sec, Temperature - 336

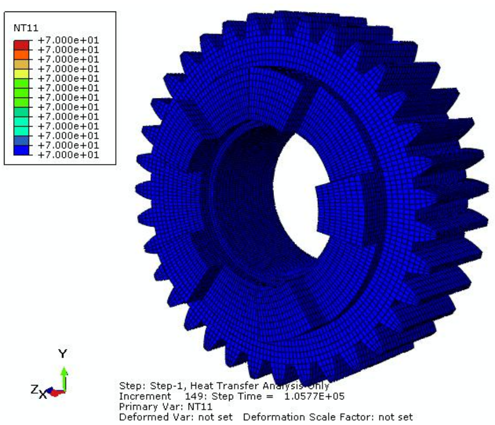

Fig. 10. At Time-100000 sec, Temperature-70 ºC

B.1.2 Stress Contours by Quenching Analysis

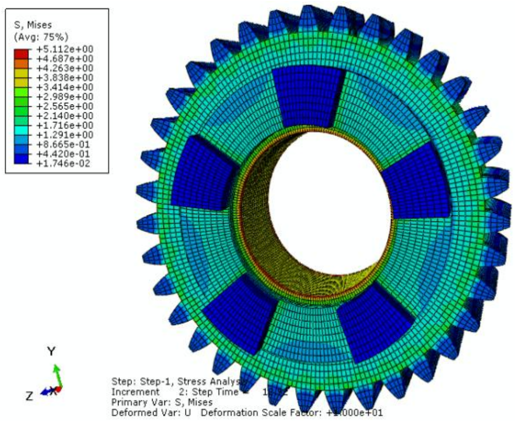

Fig. 11. At Time-12 sec, Stress-5.112 Pa

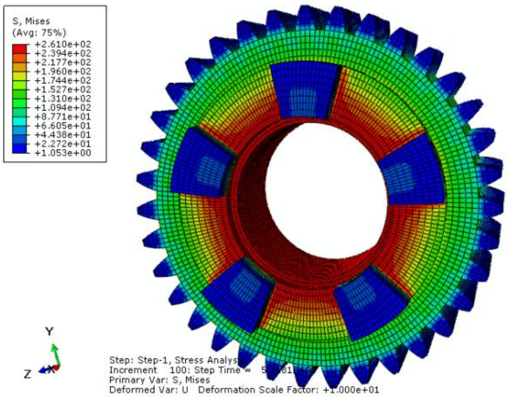

Fig. 12. At Time-52000 sec, Stress-261 Pa

B.1.3 Deformation Contour by Quenching Analysis

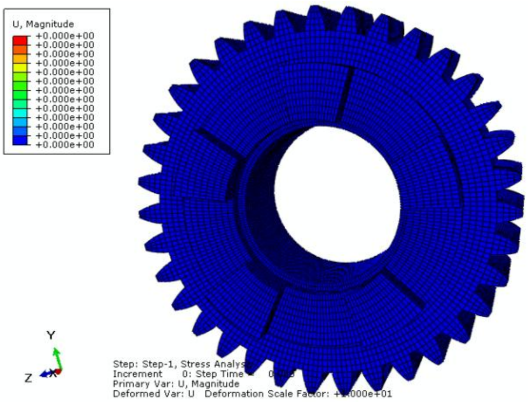

Fig. 13. At Time-0 sec, Deformation-0 m

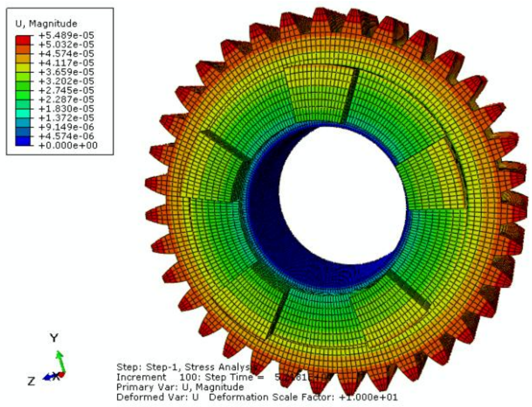

Fig. 14. At Time-52000 sec, Deformation-5.489e-5 m

IV. RESULT OF QUENCHING PROCESS

A. Thermal Transient Analysis

Table III
Time - Temperature Table

Time (sec)	Maximum Temperature (^{0}C)	Minimum Temperature (^{0}C)
0	840	840
7	838.8	830.6
50	820.4	809.9
100	803.9	793.6
500	666.3	657.9
1000	531	524.5
1500	422.4	417.5
2000	340.5	336.78
5000	124.2	123.4
10000	74.09	74.03
20000	70.21	70.21
30000	70.03	70.03
100000	70	70

B. Stress Analysis

Table IV
Time-Stress Table

Time (sec)	Maximum Stress (Pa)	Minimum Stress (Pa)
0	0	0
6	2.15	0e008
12	5.1	0.017
22	10.67	0.029
59	32.46	0.10
92	52	0.16
140	80.62	0.18
214	108.3	0.18
500	126	0.3
1000	168	0.63
2500	227.3	0.857
10000	261	1.08
52000	261	1.05

Table V
Time-Deformation Table

Time(sec)	Maximum Deformation(m)	Minimum Deformation(m)
0	0	0
6	$2.42*10^{-7}$	0
12	$4.44*10^{-7}$	0
25	$7.41*10^{-7}$	0
60	$1.83*10^{-6}$	0
91	$2.8*10^{-6}$	0
140	$4.22*10^{-6}$	0
200	$6.28*10^{-6}$	0
500	$1.33*10^{-6}$	0
1100	$2.56*10^{-5}$	0
2500	$4.16*10^{-5}$	0
10000	$5.47*10^{-5}$	0
52000	$5.48*10^{-5}$	0

A.1 Graphs- Temperature profile

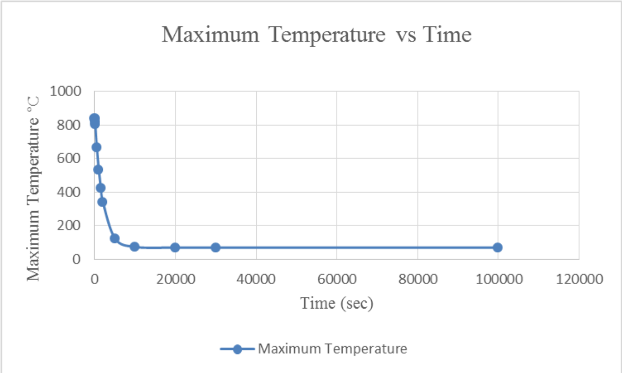

Fig. 15. Variation of Temperature with time

B.1 Stress - Analysis of non-linear gear material

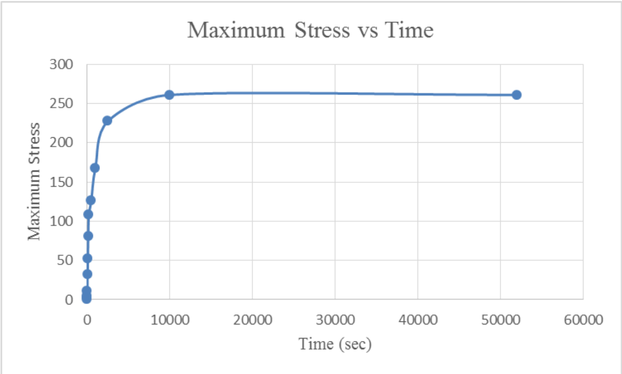

Fig. 16. Variation of Stress with time

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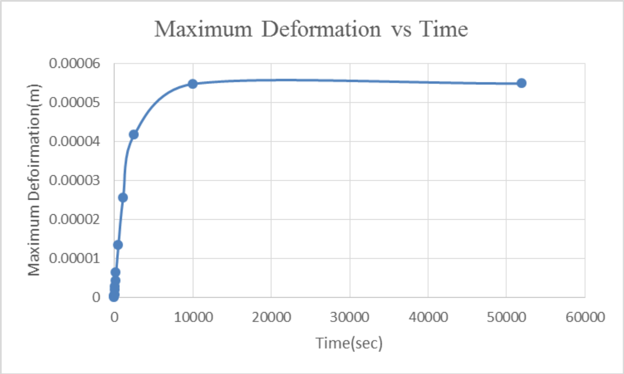

Fig. 17. Variation of Deformation with time

V. CONCLUSIONS

- From the graphs it can be easily concluded that the temperature decreases rapidly during initial stage of quenching and later tends to become constant.
- The maximum stresses and deformations increase rapidly in earlier stages and becomes constant at the later stage.
- The stress, temperature and deformation contours plotted in the software show that effects are maximum at the tips of gear and minimum at the core.
- The values of stresses and deformations are well within limits considering the data provided from the organization.
- The temperature decreases rapidly in quenching analysis and the maximum temperature values are less for this analysis. Stability of temperature is also achieved earlier in this case.
- The high temperature of carburizing results into phase change which causes deformation. Austenite formation during quenching results in generation of stresses and it also makes the gear a little soft and affects hardenability.
- The heat flows radially outwards so stress is more prominent at the tips.
- The temperature ranges during carburization are very high because of which material yields and hence non-linear physical properties can be observed.

REFERENCES

[1] S. P. Wadkar, Simulation of Low Pressure Carburizing and High Pressure Gas Quenching Process Using ABAQUS for finding distortions in component, World Congress on Engineering and Applications, WCEA–2016, Bangkok, pp. 28-33.
[2] Wang Yan-zhong, et. al. “Heat treatment process optimization for face gears”, Vol. 14 No. 1, March 2015 Journal of Chongqing University, 2015, pp. 9-18.
[3] Dr. Volker Heuer and Dr. Klaus Löser, Low Distortion Heat Treatment of Transmission Components, AGMA Technical Paper, 2010, pp. 3-16.
[4] Isaiah Paul Janzen, “Modelling of Heat Treating Processes for Transmission Gears”, report, Worcester Polytechnic Institute, 2009.
[5] A. Freborg, B. Ferguson, Modelling Heat Treatment for Characterizing Distortion, Residual Stress, Loading Response and Fracture in a Vacuum Carburized and Gas Quenched Steel Coupon, ASM International, 2014.
[6] Jeevan P, George, Justin Koshy, Distortion Reduction in Gear Heat Treatment Process by a Simple Fixture, International Journal of Emerging Technology and Advanced Enginerring, Volume 4, Issue 11, November 2014, pp. 306-312.
[7] Marcel Suliteanu, Minimizing Gear Distortion During Heat Treating, Gear Technology, April 1996.
[8] Ekkard Brinksmeier, Distortion minimization of disc for gear manufacture, International Journal of Machine Tools & Manufacture, Volume 51, Issue 4, April 2011, pp. 331–338.