Proceedings of the 8th Seminar of the International Federation for
Heat Treatment and Surface Engineering
IFHTSE 2001
Dubrovnik- Cavtat, Croatia, 12 – 14 September 2001

INVESTIGATION ON DEFORMATION OF GEAR FOR AUTOMOTIVE APPLICATION CAUSED BY CASE HARDENING

G. Casalino[1], L. Cautero[1], L.A.C. De Filippis[1], A.D. Ludovico[1], D. Longo[2], C. Maselli[2]
[1]Politecnico di Bari, Dipartimento di Ingegneria Meccanica e Gestionale, Viale Japigia, 182, 70126 BARI, ITALY.
[2]Getrag S.p.A. Italia, Via dei Ciclamini, Modugno (BA), ITALY

ABSTRACT
The case hardening is a topical step of gear manufacturing for automotive application. It is usually divided into two parts. Firstly the gear is vacuum carburized then is quenched with high pressure gas. Since the functionality of the gear box is highly influenced by the dimensional precision of gears, the design of the process mainly consists of the control of the deformation caused by the thermal cycle. For a fixed furnace, the main process parameters are the temperature, the pressure, the carburizing medium, the quenching cooling rate and medium.

In the Getrag plant of Bari, heat deformations during case hardening have eventually been under control after a deep investigation. On the basis of preliminary experiments, a plan of experiments was designed and the most important parameters varied at the same time. In this way it was possible to evaluate the effect of their contemporary variation on the deformation. After setting the rough ranges for the studied parameters, the deformation of gear was within the range proposed by the DIN standard. Nevertheless, it was still necessary to deal with a manufacturing drawback entailed with grinding the teeth. Due to the planarity error caused mostly by the case hardening which altered the correct position on the machine, the grinding of teeth was often inadequate. The consequences were an increase of grinding time. Therefore a deeper investigation was carried out. It was supported by a new plan of experiments that took into account the hardenability of the material and numerical simulation using the Systus FEM software.

Even if, the chamber geometry of the furnace has limited the efficiency of the proposed receipts for case hardening, the results of investigation produced finer range for process parameters.

Keywords: Case-Hardening, Numerical Simulation, FEM-Sysweld

INTRODUCTION

Case-hardening consists in a combination of hardening techniques, which are primarily used for highly stressed shafts, driving gears, guiding rails, and other machine components. The basis for this procedure is carburization in a carbon-emitting medium at temperatures of up to 950° C. After the desired enrichment of the component surface with carbon has been achieved by means of diffusion, the components are hardened and then quenched.

As a result, the components manifest a high degree of solidity and surface hardness (up to 800 HV), a high resistance to wear, and a high core ductility. In addition internal stress within the surface layer ensures a substantial increase in the endurance and reversed fatigue strength [1].

Large, ring-shaped components such as gears and roller bearing collars are often case-hardened. Size variations are inevitable due to this combined technique and to hold the costs of reworking at a minimum, the Getrag, gear box Plant, has carried out numerical and experimental detailed studies on size variations and hardenability during case-hardening and successive direct quenching of gears for automotive gear boxes.

Variations in size were registered in the case of alloyed case-hardening steels (12NiCrMo7) the material that is used for gears for automotive application in order to ensure a sufficient degree of hardening depth. The variations in size that occur during hardening have their origin in the material, the process, and the components

Moreover, in the furnace used at the Getrag plant of Bari, the gears appear to cool off differently due the position occupied inside the furnace, this produce an higher degree of warpage. In particular, they bent apart asymmetrically and shaped into a banana-like geometry. This deformation caused trouble during successive regrinding of the gear.

This paper reports the result of a deep investigation on the major variable affecting the gear warpage. The selected variables were the stress induced in the gear by before-carburizing machining, the hardenability of the used steel, the quenching parameters, and the position of the piece in the rack. The experimental campaign was carried out in order to evaluate the single variables effects and their interactions. Therefore, a full factorial experiment was performed following the rule of Design of Experiments (DOE).

The results were used to select narrower-then-before range of process. The influence of previous machining operations on warpage was demonstrated.

In the end, on the basis of hardness test in the transverse cross section of the gear, a numerical model was set up using Finite Element Analysis. Applying different thermal loads on the gears surfaces the effect of different cooling speed can be demonstrated and by trial-and-error method the actual thermal load during cooling can be extrapolated. The numerical model was validated on the basis of numerical against actual deformation comparison.

EXPERIMENTAL SET-UP

EXPERIMENTAL DEVICE

Furnaces for continuous hardening of gears are used at the Getrag plant of Bari.

The furnace, mod. ICBP 600 Carbon low pressure injection produced by E.C.M. Grenoble (Fr), had 6 carburising cells and 1 central direct quenching cell, which occupies a central position respect the other cells. The maximum load is about 200 kg, the range of pressure is from 5 to 20 bar and the highest temperature is 1250°C. The furnace is water cooled. The load and unload cells are sealed.

The gears are packed on special graphite racks, which are reported in Figure 1.

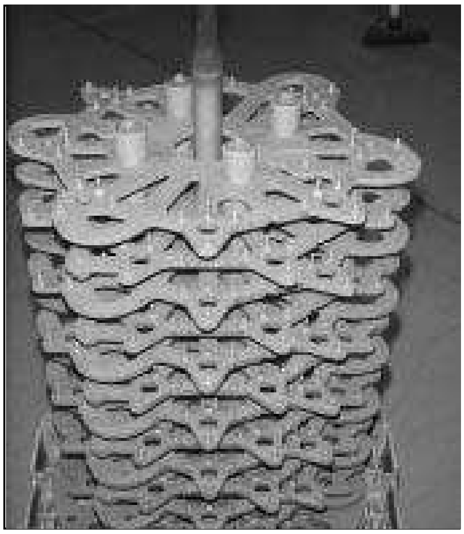

Figure 1: graphite rack

The carburising units use Propane and Nitrogen (C_3H_8) for heating and enriching gas in carburising at 950°C.

Five nozzles inject the Propane and the Nitrogen alternatively. The racks rotate in order to homogenize the heating temperature of each gear.

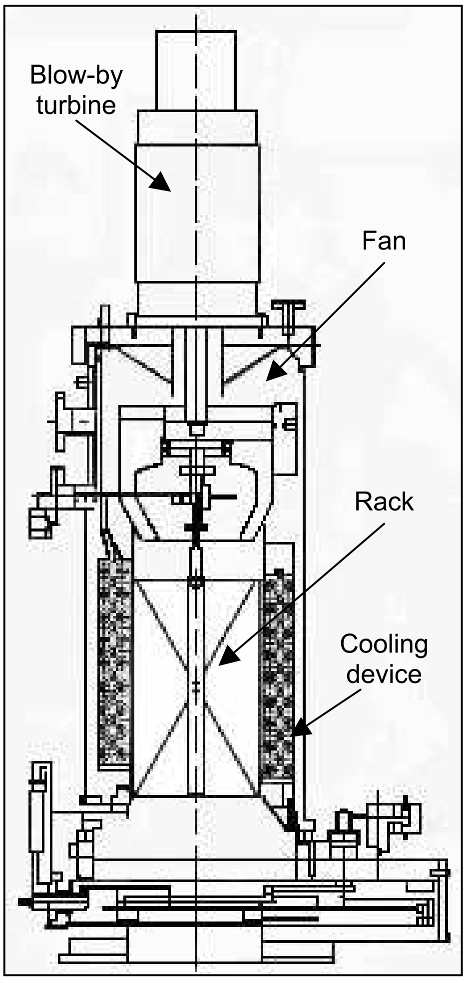

Figure 2: quenching cell

After carburised the gears are direct quenched by a Nitrogen gas. The quenching cell, which is shown in Figure 2, has a blow-by turbine for gas and a folding over cooling device. The cooling time is about ten minutes. The door, positioned at the bottom, is sealed and assures a maximum pressure of 20 bar. As a last step of the hardening process, the gears are tempered in an another furnace.

DESIGN OF THE EXPERIMENTS

In order to evaluate multiple factors simultaneously, full factorial design analysis has been performed. Analysis of variance (ANOVA) for results was performed using a commercial statistical analysis package, MiniTAB [2]. The performed design has been a balanced full factorial and it has provided information about both the main effect and the higher-order interactions among factors related to gear hardening. The selected factors and their levels were the stress induced in the gear by before-carburizing machining, the hardenability of the used steel, the quenching parameters. In particular, the effects of the hobbing, the welding of synchronizer, and the cleaning

were singularly evaluated by hardening several sample just after each machining. Four casts, with slightly different chemical content, were tested. The equivalent carbon varied from 0.613 to 0.624. Two pressures (15 and 17 bar) and two temperatures (880°C and 950°C) were used for quenching.
Moreover, the position of gear in the rack was considered. In fact, the gear warpage at three different positions were measured. The position were the lowest, the midst, and the highest with respect to the rack geometry. In this way the influence of geometry of furnace on gear hardening was qualitatively evaluated. Table 1 shows the overall of the factors and their levels.

Table 1: factors and levels of experiments

Machining	Chemical content	Pressure (bar)	Tempearture (C)	Position
Hobbing, Welding, Cleaning	0.613-0.624	15-17	880°-950° C	Highest Midst Lowest

RESULTS OF THE EXPERIMENT

The amount of warpage was evaluated in terms of error of planarity. That was estimated at a certain diameter of the gear after the hardening process was over (see Figure 3). The error of planarity is the biggest difference between the actual profile and a reference plan. Figure 4 shows the error of planarity for a rear gear of 5 speed gear box. The position of the gear in the rack is the midst. For that gear the error of planarity was 0.0379 mm while the tollerated one was 0.0200 mm (DIN standard). The Zeiss 3D contact CMM machine was used for measurement.

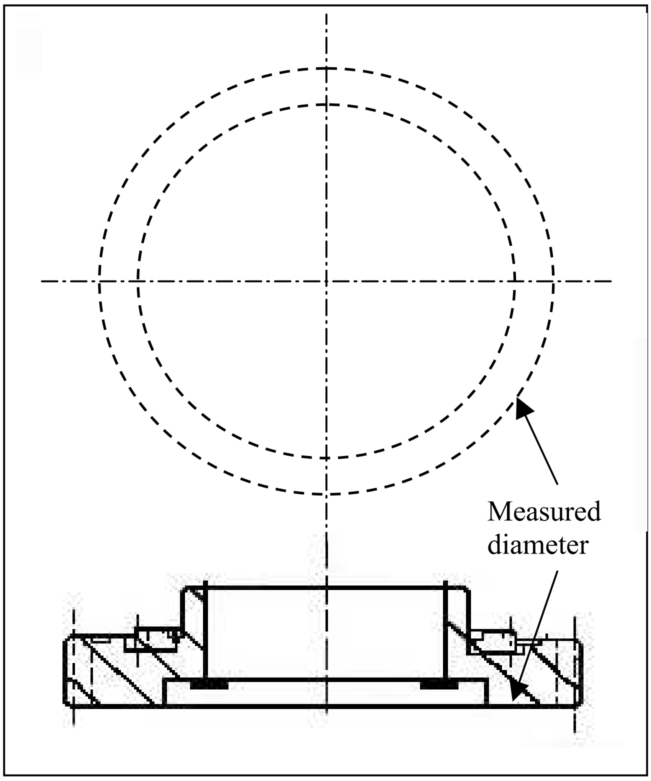

Figure 3: measure position

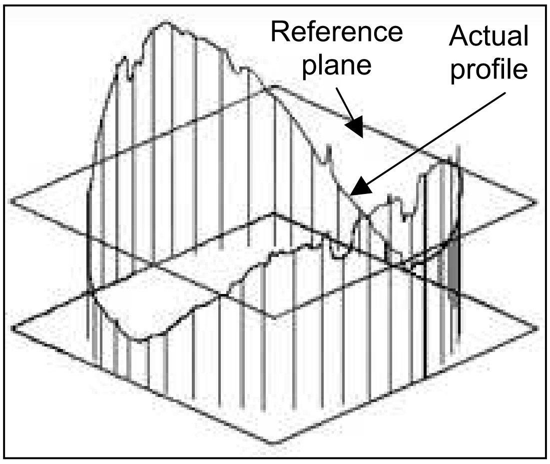

Figure 4: error of planarity

On the basis of the estimation of the marginal means [3] some important results have been obtained. The position of the gear in the rack strongly affects the amount of deformation. In Figure 5 the number 1 refer to highest position in the rack, number 13 to the lowest, number 7 to the midst position. The position 1 was directly exposed to the cooling flow on the other hand the position 7 and 13 were covered by the dishes above. The influence of the quenching temperature and pressure is showed in Figure 6. Both the variables and their interaction are significant. In particular, the best combination of the two parameters seems to be the highest temperature and pressure.

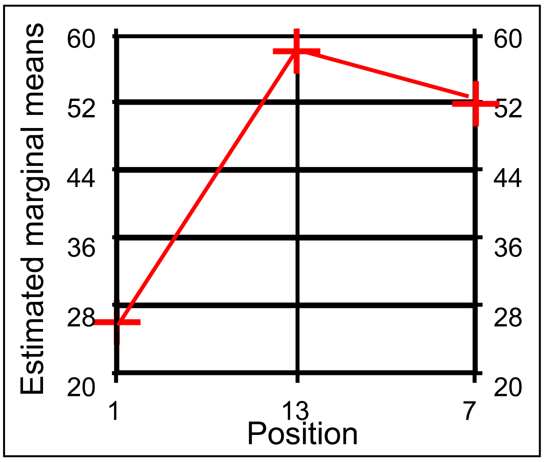

Figure 5: estimated marginal means of position in the rack

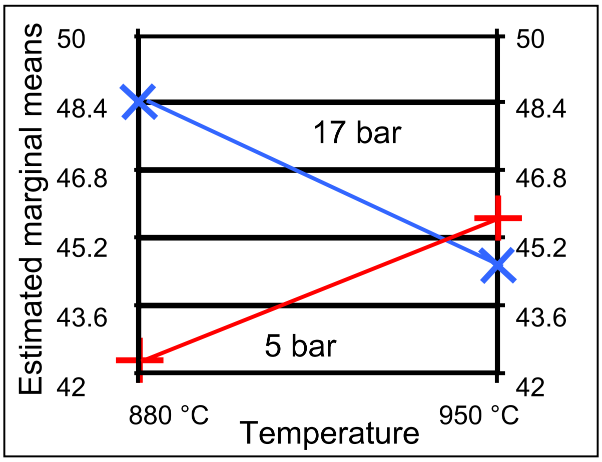

Figure 6: estimated marginal means of temperature/pressure interaction

It was proved that the deformation arose with the stress induced by previous machining. In particular a significant difference was found between gear before and after the welding of the synchroniser device, which is also a slightly different kind of steel. About the carbon and alloys content in the steel used for gear, it was showed that the less the hardenability of the steel the low the deformation induced during the hardening process.

NUMERICAL SIMULATION

PRINCIPLES

Today, finite element method is widely used for modeling heat treatment and surface hardening processes in order to reduce the number of experiments which will be done only for the final validation of the product or the process.

Such simulations must take account of complex interactions between several physical phenomena such as heat transfer, metallurgy, mechanic and the diffusion of chemical elements. So, they provide the complete evolution of all the physical quantities which govern the process and which, for most of them, can't easily be measured. Therefore, the user has a full understanding of the process which enables optimization.

Figure 7: rear gear

The authors modeled the coupled carbon diffusion, heat transfer and metallurgical transformations analyses for the simulation of heat treatment of rear gears (Figure 7).

The simulation is performed in two steps (Figure 8). First a diffusion analysis at constant temperature is achieved in order to compute the carbon content at any point in the component. Then a fully coupled thermal and metallurgical analysis is done.

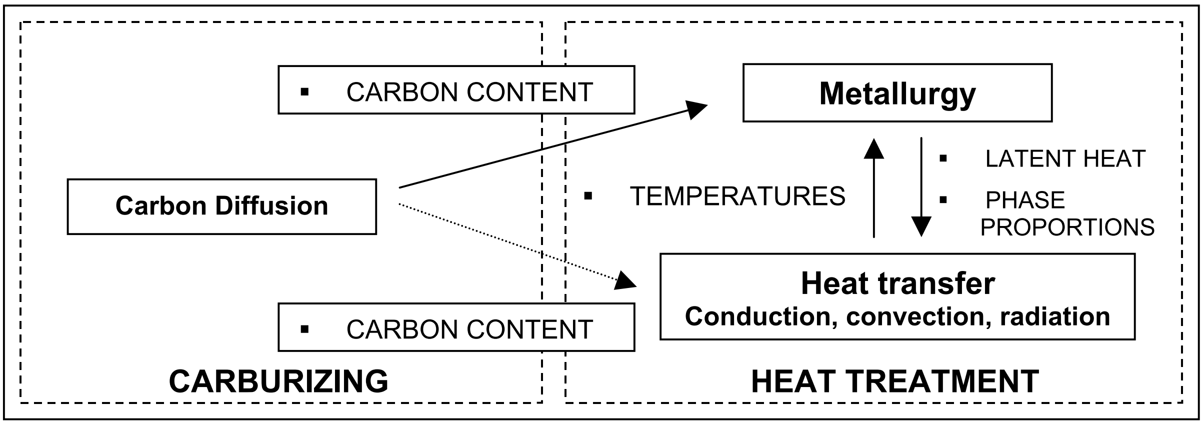

Figure 8: Couplings between physical phenomena (coupling indicated with a dotted line is neglected

Since hardening causes a change in structure and presupposes that suitable - hardenable - materials are used [4]. The maximum increase in hardness is obtained when the structure mainly consists of martensite.

After austenitising, cooling has to take place at a rate sufficient for the required hardening, so that transformation preferably takes place in the martensite range. Transformation into the hardening structure martensite occurs when the martensite start point M_s is reached in fractions of seconds as a diffusion-less shear process of the cubic face-centred iron lattice into a body-centred cubic lattice. The carbon atoms previously dissolved in the austenite remain in their interstitial lattice positions and distort the corresponding body-centred cubic lattice into a tetragonal structure. This the reason for the relatively high hardness of the martensite structure and also causes an increase of volume.

GEAR MODEL

Numerical simulation has been conducted with Sysweld, a commercial software dedicated to welding and heat treatment FEM modeling [5]. As a first approximation of the actual model, the authors used a 2D ax-symmetric model. Mechanical constrains were imposed at the inner diameter of the gear. Numerical results were compared with the experimental tests.

The process that has been modeled is the following:

- Stage 1: Case-hardening;
- Stage 2: Gas Quenching.

The considered material is a low-alloy carbon steel (12NiCrMo7) with 0.2% of carbon. The following phases and relative transformations were considered: Austenite, Ferrite, Perlite, Bainite, Martensite, Transition carbides (stands for the precipitation of transition carbides during tempering and self-tempering), cementite (stands for the trasformation of transition carbides into cementite on tempering), Cementite+Ferrite (stands for the transformation of retained austenite in ferrite+cementite on tempering).

GEOMETRY AND MESH

Simulation of internal stresses and distortion of practical components by means of finite elements initially requires that the component is meshed with finite elements on the basis of the component geometry generated in a CAD system.

In this case only an half part of the 2D section has been considered, for symmetry reasons, and meshed.

Because of the highest thermal gradient, a more fine mesh is modeled in the external region whereas a coarser mesh was used in the other part of the plate. Figure 9 shows the geometric model of the gear's 2D section and the mesh used for simulating the process. This kind of mesh is necessary in order to evaluate the percentage of martensite.

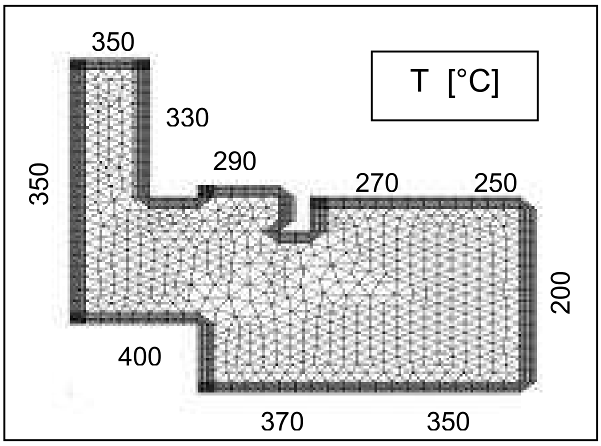

Figure 9: geometrical model and quenching temperature

THERMAL MODEL

For the case hardening, the carbon percentage is computed using the diffusion-precipitation model of Sysweld. Standard diffusion data from literature have been used. Boundary conditions have been adjusted in order to reproduce the experimental results. The carburizing temperature was 950°C.

Carbon content computed in the previous stage is the input for the thermo-metallurgical analysis of quenching. This percentage is used for the computation of metallurgical transformation.

Figure 10: phase percentages after cooling

In Figure 10, the percentage of different phases is plotted for the transverse section. As expected, for this process, the outer part contains only martensite and retained austenite. The significant amount of retained austenite is correlated with experimental data. The inner part of the gear is mainly ferrite with a small amount of martensite.

The direct quenching was simulated in two different step. During the first step the temperature lowered from 950°C to 250-400°C (see Figure 9), in the other the temperature collapsed to 50°C. By imposed different thermal loads on the gear, the not homogeneous cooling was simulated with a good approximation to the actual cooling. This was proved by the obtained final phases (Figure 10) and the actual geometrical warpage of the gear (Figure 11).

MECHANICAL ANALYSIS

The temperatures calculated during the thermo-metallurgical analysis were used for computing the geometrical warpage of gear. Figure 11 shows the deformation along the z-axis at the end of quenching. The draw in Figure 11 is magnified 100 times.
It is evident the banana-shape, which is the typical result of quenching this kind of gear in the furnace used in Getrag plant of Bari.
The planarity error can be easily read at the correspondent diameter. In this case the value is about 0.04 mm which is in agreement with the measure obtained with the Zeiss CMM.
Different kind of cooling rate can be simulated by modifying the thermal load during quenching. Nevertheless, a correct knowledge of the cooling flow would bring to better result. Therefore a deeper flow analysis is necessary.
Moreover, the 2D model is inadequate for a reliable prediction of warpage. In fact, the hypothesis of ax-simmetric deformation is valid only for a rough investigation.

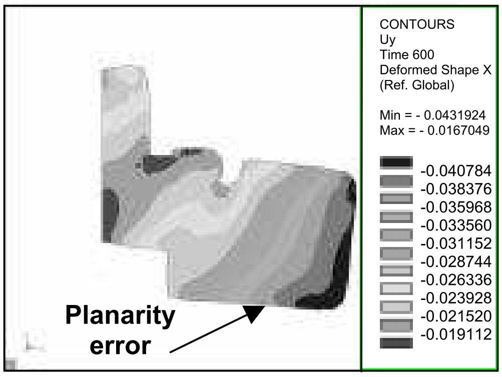

Figure 11: distortions after quenching

CONCLUSIONS

This paper deals with the warpage induced by the hardening process of gear for automotive application. In the first part, the hardenability of the steel, the pressure and the temperature of quenching, the position of gear in the rack during the heat treatment, and the stress induced by previous machining and welding were investigated. It was found that the position of the gear in the rack strongly affects the gear warpage. The gear positionated at the lowest level of the rack shown the higher deformation. The pre-stress induced by machining and welding induced higher warpage. Interaction between temperature and pressure shown that higher temperature and pressure reduced deformation. Last but not least, the higher the hardenability the higher the warpage.
In the second part, a FEM 2D numerical model was built. It firstly considered the thermo-metallurgic transformation and thereafter the mechanical deformation. In this way a reliable computation of error of planarity was performed. Further development will be a 3D model of the gear and a quantitative evaluation of cooling flow.

REFERENCES

[1] ASM. Heat Treatment Cleaning and Finishing. Metals Handbook.
[2] Minitab release 13. Product of Minitab Inc. 2000.
[3] Montgomery. Design and Analysis of Experiments. John Wiley & Sons, Inc.
[4] Avrami M., J. Chem. Phys., 7, pp. 1103, 1939. J. Chem. Phys, 8, pp. 212, 1940.
[5] SYSTUS Inter., SYSWELD 2000 Reference Manual, ESI Group, Paris(1999).