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A STUDY ON DISTORTION OF BEVEL GEARS AND DIE INDUCED BY FORGING AND HEAT TREATMENT

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ABSTRACT

Recently many kinds of gears have been produced by forging in order to enhance the mechanical properties of the gears and the productivity of the process. Developments in forging technology are the reason for the increased usage. However, a critical problem of the forged gears is the dimensional change or distortion caused by elastic recovery after forging, and relief of the residual stresses during subsequent heat treatments. Distortion is of great concern to the manufacturers of precision parts, because it influences directly the dimensional accuracy and the grade of carburized bevel gears. In the present paper, distortion due to cold forging and heat treatment of bevel gears is investigated. Distortions of forged gears, machined gears and die are measured and compared. Numerical analysis is used to simulate the complete cold forging process and heat treatment process for the machined gears and shows good agreement with the experimental measurements.

Keywords : Elastic recovery, Cold forging, Heat treatment, Distortion, Bevel gear, FEM

1 INTRODUCTION

Bevel gears are widely used in the automotive industry and are manufactured by either machining or forging. The production ratio of forged gears to machined gears is increasing because forging enhances the mechanical properties of the gears and is a more productive process. However, the disadvantage of forged gears is the dimensional change or distortion caused by elastic recovery after forging and by relief of residual stresses during heat treatment. Distortion of the product critically influences the dimensional accuracy of precision parts. The prediction of distortion during heat treatment is very difficult and has generally been done based on prior experience or by a trial and error approach.

Heat treatments are widely used in various manufacturing processes to enhance the quality of a product such as strength, surface hardness, and service life. In order to get the desirable combination of microstructure, material properties, residual stresses and dimensional accuracy in the final product, a heat treatment process may involve several heating and cooling steps, and include carburizing and diffusion processes.

With the development of computer modeling techniques, it is possible to detect and correct potential problems such as distortion during forging and heat treatment. Lee *et al.* [1] calculated the elastic deformation of die with reinforced ring. Majorek *et al.* [2] investigated the influence of heat transfer on the development of residual stresses and of changes in dimension and shape after quenching in two medium carbon steels. Krauss [3] reviewed the evolution of the processing-dependent microstructures and residual stresses in carburizing steels, and the relationship of microstructure and residual stress to fatigue performance of carburized steels. Inoue *et al.* [4] developed a CAE system to simulate heat treatment.

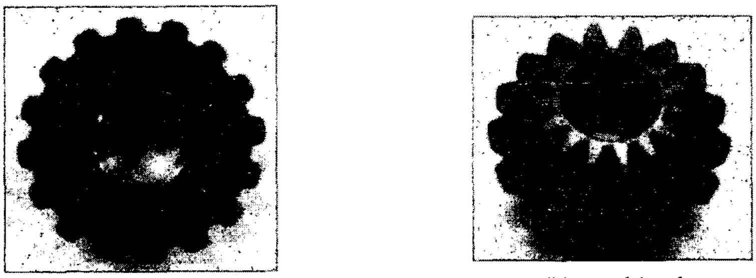
The objective of the present research is to investigate the distortion of die and workpiece during cold forging and heat treatment of a forged bevel gear. Any measurable and consistent distortion should be compensated for when the forging die is designed. In this study, distortions of straight bevel gears made from SAE 4118H were studied by both experiments and numerical simulations. Finite element analysis was performed to simulate the forging process and die deformation, and to predict the microstructure and distortion for a machined gear during the entire heat treatment cycle.

2 MEASUREMENT OF DISTORTION

The composition for the SAE4118H bevel gear used in the current work is given in Table 1. A three-dimensional scanner that has a resolution of 1μm was used to measure the distortion. Figure 1 shows the forged and machined straight bevel gears and the specifications are given in Table 2. The heat treatment steps are shown in Figure 2.

Table 1. Chemical Composition of SAE4118H

Material	C	Si	Mn	P	S	Ni	Cr	Mo
4118H	0.2	0.22	0.75	0.13	0.19	0.01	1.00	0.25



(a) forged (b) machined

Fig. 1 Configuration of bevel gears.

Table 2. Specification of straight bevel gear

No of teeth	16
Module (mm)	5.0
Pressure angle	22.3
Pitch diameter (mm)	80.0
Pitch angle	58.00

The measurement locations on the gears are shown in Fig. 2.

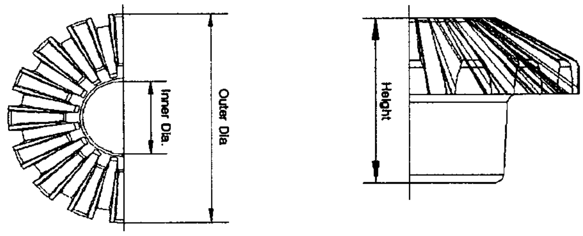


Fig. 2 Measurement locations on the bevel gear.

2.1 Distortion of Elastic Recovery

Processes of cold forged bevel gears are consist of perform forming, tooth forming, and sizing. The first stage is to form the initial billet into a proper perform for the effective forging of complex geometry. After performing, the preformed workpiece is formed again into the final part in the second stage, which is forming the involute tooth [5]. The last step of process, sizing, make it to be precise [6].

Forged bevel gear and die are measured by 3D-SCANNER on same position. Total elastic distortion is a difference between bevel gear dimension and die dimension. Table 3 show the comparison of total elastic distortion between die and bevel gear [7].

Table 3. Comparison of total elastic distortion between die and bevel gear (mm)

Measured position	Outer diameter	Inner diameter	Height
Die dimension	81.936	30.029	18.377
Gear dimension (avg.) after forging	82.092	30.223	18.456
Total elastic distortion	0.156 (0.190%)	0.194 (0.646%)	0.073 (0.243%)
Distortion direction	outward	outward	outward

2.2 Distortion of Heat Treatment

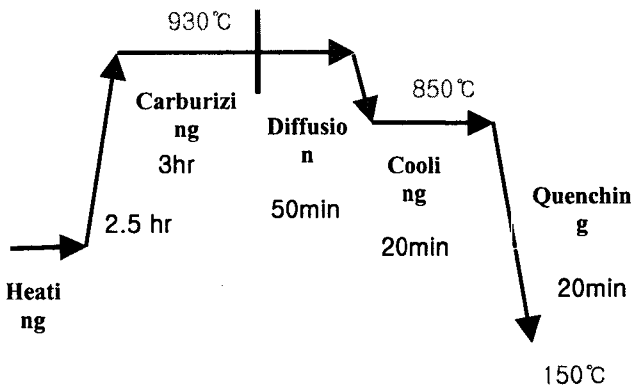


Fig. 3 Heat treatment steps for the bevel gear.

The factors affecting distortion in forged bevel gear are (1) movements due to the relief of residual stresses induced by forging, (2) volume changes due to phase transformations and (3) deformations caused by non-uniform heating and quenching. In this paper, two cases of the heat treatment of forged gear were measured and compared. In the first case, the distortions after the heat treatment steps were compared between forged bevel gears and machined bevel gears. The distortion of a machined bevel gear was compared with the simulation results from DEFORM-HT. In the second case, the distortion after carburizing, diffusion and a very slow cooling was measured to determine the amount of distortion due to the relaxation of residual stresses.

Tables 4 show the distortion induced by the heat treatment steps for the forged gears and the machined gears, respectively. The outer diameter (OD) and height of both types of gears increased after heat treatment, but the inner diameter (ID) of the forged gear was reduced. The amount of dimensional changes of the OD on the forged gears was larger than the machined gears.

Table 4. Distortion induced by heat treatment

Measured location	Forged Bevel Gears			Machined Bevel Gears		
	OD	ID	Height	OD	ID	Height
Before HT (mm)	82.053	30.803	39.569	81.889	30.799	39.680
Average distortion (mm)	0.046	-0.014	0.018	0.024	0.015	0.025
Distortion ratio (%)	0.056	0.046	0.046	0.0293	0.0487	0.0630
Deviation (mm)	0.009	0.006	0.008	0.005	0.005	0.007

Table 5 gives a comparison of the distortion induced by slow cooling after the heat treatment steps (called annealing) versus quenching. The ID of the forged gear contracted and OD expanded during annealing due to the relief of residual stresses. The number of samples that were measured ranged from five to ten. The standard deviations for the distortions in the forged gear were relatively small. However, the standard deviations for the forged gears were larger when compared to the machined gears.

Table 5. Comparison of distortion induced by annealing and quenching processes

Heat treatment	Annealing		Oil-quenching	
Measured location	OD	ID	OD	ID
Before HT(mm)	82.054	30.796	82.050	30.800
Average distortion(mm)	0.022	-0.020	0.040	0.011
Distortion ratio(%)	0.0268	0.0649	0.0488	0.0357
Deviation(mm)	0.008	0.005	0.008	0.002

3. SIMULATION AND RESULTS

3.1 Simulation of Elastic Recovery

Deform-3D and Ansys-5.7 were used to simulate the forming process in order to predict distortion induced by elasticity of bevel gear and die.

Table 6 shows comparison of distortion between measurement and simulation. Die is assumed as two cases, rigid and elastic.

Table 6. Comparison of distortion between measurement and simulation

Measurement position		Inner diameter	Outer diameter	Used tool
Final deformation by Experiment(A)		0.194	0.156	3D Scanner
Elastic deformation of gears by simulation(B)		0.11	0.14	Ansys
Rigid Die assumption	Die deformation(C)	0.009	0.036	Deform 3D
	Total (D=B+C)	0.119	0.176	
	Deviation (D-A)	-0.075	0.02	
Elastic Die assumption	Die deformation(E)	0.061	0.134	Deform 3D
	Total (F=B+E)	0.171	0.274	
	Deviation (F-A)	-0.023	0.118	

3.2 Simulation of Heat Treatment

DEFORM-HT was used to simulate the heat treatment and quenching processes in the machined gears. The convective heat transfer coefficient used in the simulation was a function of surface temperature for oil quenching and it was 50W/m^2 K during the heating step [2].

The finite element mesh with 4066 nodes and 16567 brick elements used in the simulation of 1/32 of a gear. Table 7 gives measured and predicted distortions of the inner and outer diameters. The two sets of values are in good agreement.

Table 7. Comparison of distortion from FEM analysis and experiment

Measured location	ID		OD	
Distortion (mm)	Analysis	Experiment	Analysis	Experiment
	0.011	0.015	0.037	0.025

Figure 6 shows the time history for the deformation during quenching. It can be seen that diameter dimensions increased on heating due to thermal expansion. They initially decreased during quenching due to thermal contractions but increased later due to the martensite transformation.

Figure 7 shows the carbon content distribution as a function of depth. The content at surface is very high due to the diffusion cycle.

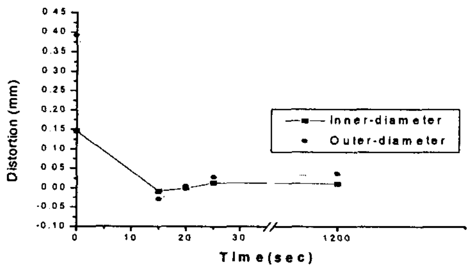


Fig. 6 Distortion during quenching.

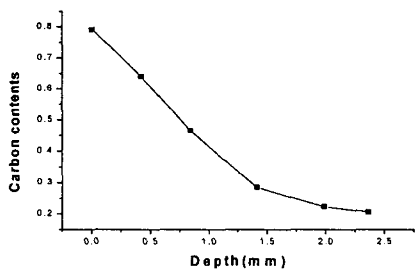


Fig. 7 Variation of carbon content with depth.

4. CONCULSION

Die and forged bevel gear were measured by 3D-SCANNER. Deform3D and Ansys5.7 were used to simulate the forging process and elastic recovery of a gear. Distortion induced by elasticity of bevel gear was larger than that of die. Simulation predicted that distortion values were a good agreement with the measured values.

The dimensional changes during heat treatment of bevel gears made by cold forging and by machining were measured and compared. Distortions after slow cooling and after quenching of forged gear were also measured. Finite element analysis was performed to predict the microstructure and distortion during the heat treatment consisting of heating, carburizing, diffusion and quenching.

Distortions of the forged gears were larger than the distortions of the machined gears; specifically the outer diameter was almost doubled. The variation is distortion values, as measured by the standard deviation, were larger for the forged gears. The simulation predicted distortion values for the machined gears were a good agreement with the measured data. Distortion due to a relaxation of the residual stress by cold forging is not negligible and needs further study. The results in this research can be used in the die design for precision forging of gears.

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