Residual Stress Measurements in Bevel Gear after Different Production Phases

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This article discusses residual stress measurements by means of electrochemical removal of material layers with residual stresses and simultaneous measurement of strain on the opposite specimen side with strain gages. Exact measurements are impossible particularly because of the small bevel gear module. With the method presented, the average residual stresses in the tooth root plane and underlying layers are measured. Residual stress distribution after each consecutive production phase is plotted and analyzed. Residual stress measurements enable the engineer to adequately assess each individual production phase and by that improve the quality of the complete production process.

Keywords
bevel gears, residual stress

1. Introduction

DURING the operation of hay pickup trailers, an unexpectedly high number of complaints were received due to fracture of the built-in bevel gear. Initially, in material and surface integrity investigations, no cause of the rupture was discovered. The production process of the bevel gear consists of several phases. In each phase, residual stresses are partially removed and new stresses are added. In the present investigation, residual stresses were measured after each individual production phase.

In the present article, measurement of the first type of residual stresses is discussed.[1,2] The method of measurement is based on deformation measurements taken on flat specimens during the electrochemical removal of the layers containing residual stresses.[3] The geometry of the bevel gear is rather complicated, and exact measurements are impossible. Nevertheless, the results of measurements on an approximated specimen shape provided some useful data for improving the production process.

Of particular interest are measurements of the tangential component of residual stresses.[4] During operation, the load on the gear tooth causes primarily tangential stresses.[5] For that reason, specimen deformation can be measured only in one direction instead of three directions.[2,6] This reduces investigation costs. By combining electrochemical removal on the front of the specimen and simultaneous strain measurements with strain gages on the back of the specimen, the authors were able to measure residual stresses not only in the thin surface layers, but also throughout the thickness of the material almost through to the back of the specimen. For the present purpose, the most important residual stresses occur in the surface of the tooth root and in the layers beneath it.[7]

2. Bevel Gear Data

A schematic of the bevel gear is presented in Fig. 1. Basic geometry data are such that $z = 40$; $m = 4$ mm; $d_0 = 160$ mm; and $b = 28$ mm. The bevel gear is made of Cr-Mo steel (JUS C.4721) with the following chemical composition.

	Composition, %
C	0.18-0.23
Si	0.15-0.40
Mn	0.90-1.20
Cr	1.10-1.40
Mo	0.20-0.30

Bevel gears were produced in several production phases consisting of forging, turning, milling, carburizing, quenching, and annealing.

3. Specimen Preparation

The authors' method for residual stress measurement is suitable for flat specimens. To obtain such a specimen, the bevel gear must be cut by means of a thin grinding wheel, which means that the residual stresses will be partially relaxed. To measure this relaxation, a strain gage is glued onto the back plane of the bevel gear and connected to the measuring chain before actual cutting occurs (see Fig. 2).

The bevel gear was cut with a 1.5-mm thick grinding wheel using gentle conditions. The cutting procedure in five plane cuts is presented in Fig. 3 to 5. The bottom surfaces were additionally polished, thus reducing the residual stresses induced by grinding to an insignificant level.

The strain gage was connected to the measurement chain during the entire residual stress measuring procedure, i.e., during the complete cutting procedure until the deformation measurements during electrochemical removal of residual stress layers were completed. The strain gage measured the deforma-

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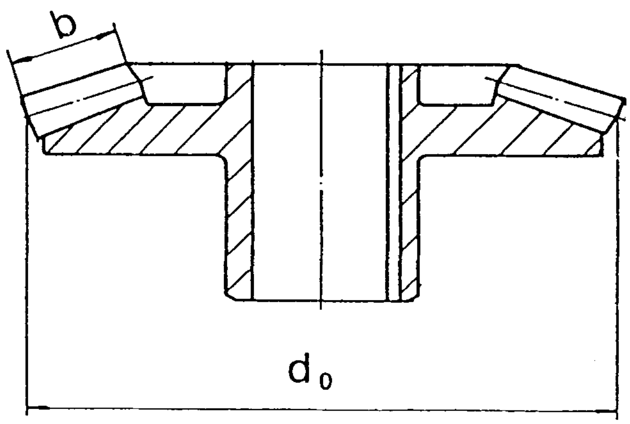

Fig. 1 Bevel gear configuration.

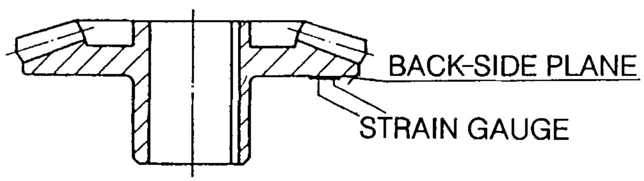

Fig. 2 Strain gage is glued to specimen surface before cutting occurs.

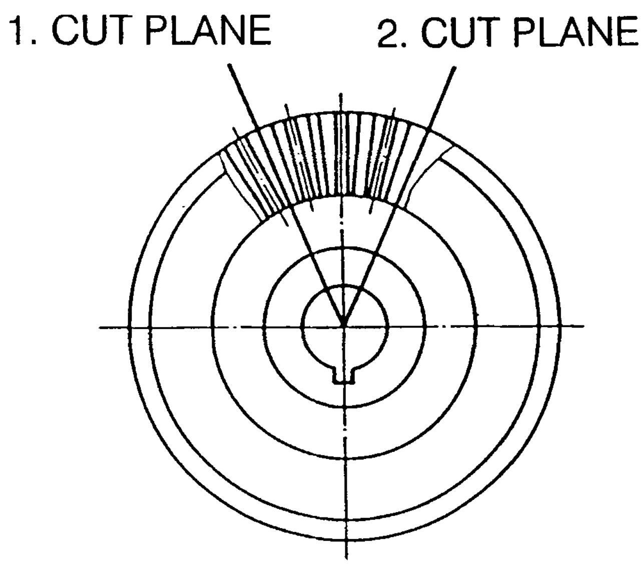

Fig. 3 First and second cut planes.

tion on the back of the specimen while electrochemical removal took place on the front of the specimen (see Fig. 6).

It was assumed that after electrochemical removal, the remaining layers contained only minor residual stresses. With the current residual stress measurement method, the author was able to calculate the original residual stresses. Individual specimens were numerically designated. For example, the specimen designated 3.1 indicates:

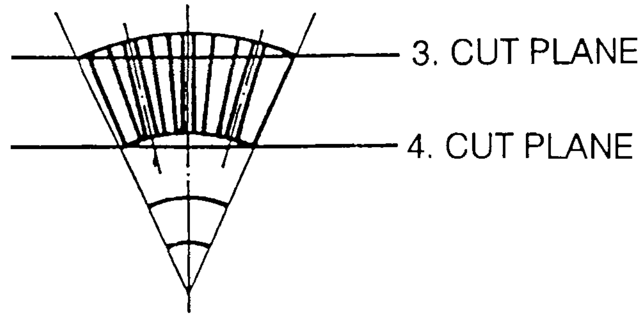

Fig. 4 Third and fourth cut planes.

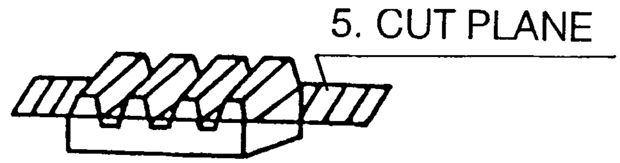

Fig. 5 Fifth cut plane is just above the root of the cogs.

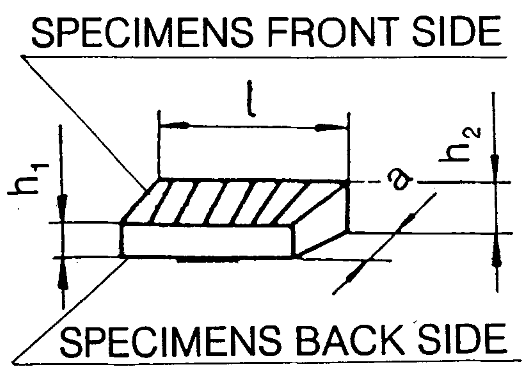

Fig. 6 Specimen shape after cutting, before electrochemical removal on the front of the specimen.

3 — Specimen was cut after the third production phase (after milling)

1 — Successive specimen number (first specimen in the group)

4. Residual Stress Measurement Results

After the first two production phases, i.e., forging and turning, residual stresses were not measured. It was assumed that these two phases could not produce residual stress states that would affect final product quality. After each of the remaining production phases, three bevel gears were cut, and the residual stresses were measured. Residual stresses were measured by means of strain measurement with a strain gage. Deformation was measured during specimen preparation by cutting it from the bevel gear, and via electrochemical removal of the front

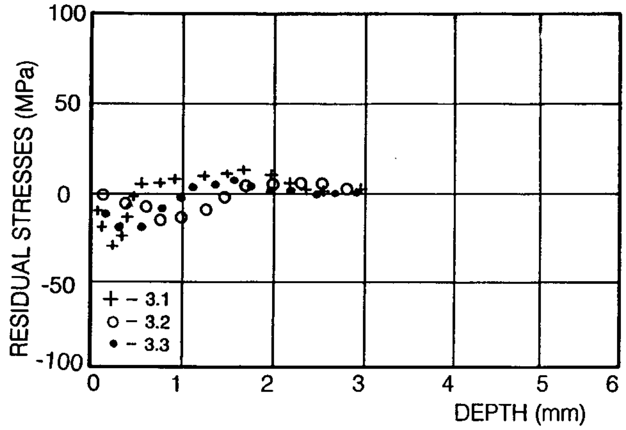

Fig. 7 Residual stresses after milling measured on three specimens.

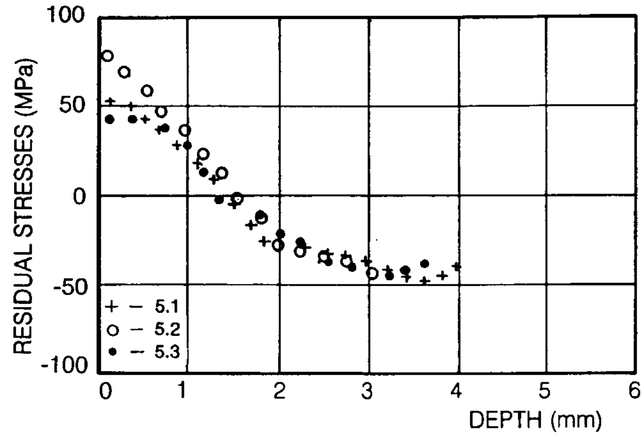

Fig. 9 Residual stresses after quenching measured on three specimens.

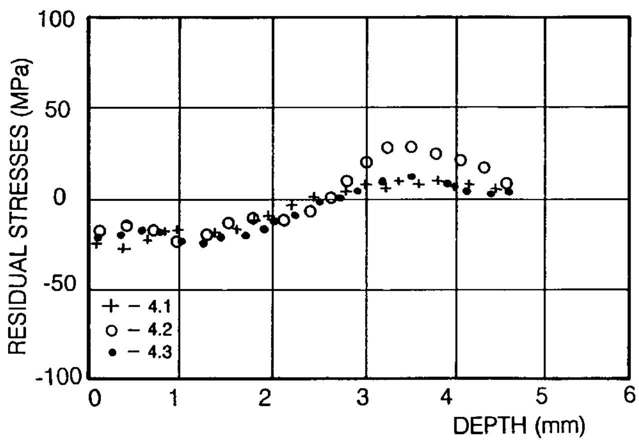

Fig. 8 Residual stresses after carburizing measured on three specimens.

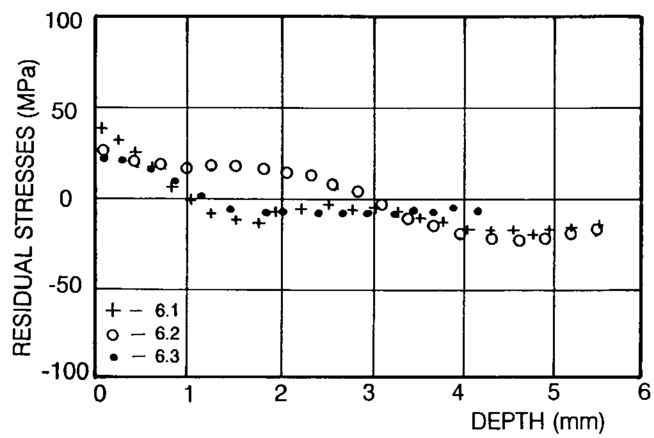

Fig. 10 Residual stresses after annealing measured on three specimens.

layers. The total deformation on the back of the specimen surface was considered. Residual stress measurement results on the three bevel gears taken after milling, the third production phase, are presented in Fig. 7.

As expected, the residual stresses in the surface layers after milling are compressive due to the cold deformation effect. In deeper layers, tensile residual stresses develop. These stresses are low in magnitude and cannot cause cracking of the surface.

The next production phase is carburizing, which takes place at 920 °C for 8 h. All residual stresses after milling are eliminated. The residual stress measurement results on the three bevel gears after carburizing are presented in Fig. 8.

Due to carbon diffusion, the surface layers contain compressive residual stresses. As a reaction, in deeper layers, tensile residual stresses are created.

The fifth production phase is quenching in oil from 870 °C. The residual stress measurement results on the three bevel gears after quenching are presented in Fig. 9. Residual stresses in the hard martensitic surface layers are not compressive as may be expected, but they are tensile. At depths greater than 1.5 mm, they become compressive. The magnitude of these stresses is not critical, but it must be remembered that average values in the front of the specimen are being taken. Concentrated residual stresses in the root of the tooth before specimen preparation must have been higher, which means that quenching is the critical phase of the production process. The majority of fractures are caused by inappropriate quenching and afterwards by incomplete annealing. During rapid cooling conditions, much higher internal stresses can develop than those that remain.

The last production phase is annealing at 190 °C. The residual stress measurement results on the three bevel gears after annealing are presented in Fig. 10. The results show a reduction in residual stresses introduced after quenching. At the surface, they are still tensile, but with low magnitude. The average residual stress measurement results for the four groups of specimens after the four individual production phases are presented in Fig. 11.

From comparison of the residual stresses after the individual production phases, one can see that quenching generated undesirable residual stresses. By annealing, the undesirable

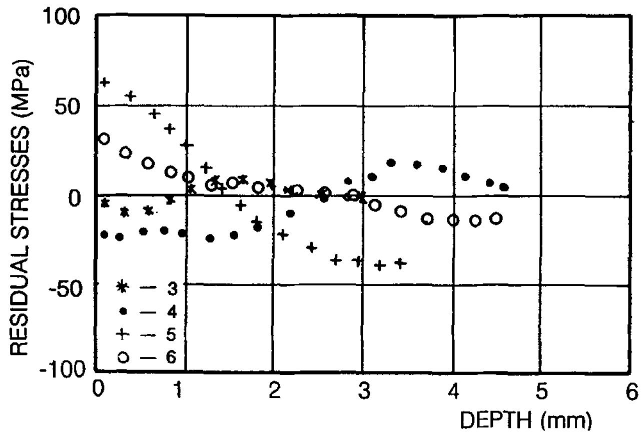

Fig. 11 Average residual stresses after individual production phases.

tensile stresses are reduced, but desirable compressive stresses are still not achieved.

5. Conclusions

The configuration of the bevel gear is too complicated for exact residual stress measurement. The results of the current measurements consist of average stresses in the front, i.e., the cone root plane and the layers beneath it. Residual stresses in the uncut bevel gear are concentrated in the tooth root radius. The average values that were obtained can only provide a relative comparison of the individual production phases. With a change in an individual parameter of the production phase, the effect of that parameter on the complete production process is established. Such a procedure enables improvement of the production process.

The results of the current measurements revealed that the reasons for bevel gear fractures lay in inappropriate execution of quenching and annealing procedures, which were performed by a cooperative firm.

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