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"As-Cast" Shape Related to Heat Treatment Distortion in Circular-Shaped Engineering Components

S. Gunnarson, M. Cristinacce, T. Lund, and J. Volkmuth

Case hardening steel has been used for the study of distortion in circular formed engineering components: gear blanks, clutch sleeves, and roller bearing rings. One melt of case hardening steel was cast in three different ways: square and round continuous billets and ingot cast. The gear blanks were manufactured by forging from 100 mm diam and 90 mm square billet. The clutch sleeves and the bearing rings were manufactured from thin-walled tubes. The gear blanks were blind case hardened; clutch sleeves and bearing rings were heat treated by conventional case hardening. All the hardening operations were conducted as free hardening. By these means, the possible influence of the as-cast mold shape upon distortion could be evaluated. Distortion assessments, mainly out-of-round, were conducted with the aid of Fourier analysis. The dominant component of the out-of-round in all the studied cases was ovality. The ovality in each case was of the same magnitude regardless of the as-cast shape. Thus the as-cast shape was not a dominating factor in the distortion of free-hardened circular engineering components. The cause of the substantial ovality in these components could not be derived in this study. However, earlier publications showed that the as-cast shape has a dominant influence on the distortion of fixture quenched circular components.

Keywords
as-cast, carburizing, distortion, heat treatment, shape

1. Background

HEAT treatment dimensional changes and distortion are probably the most thoroughly investigated parameters in the manufacture of precision heat treated engineering components (Ref 1, 2). Control of dimensional changes and low distortion in heat treatment are essential to the economical manufacture of round precision components. For this reason, the engineering details often stay as proprietary company information and, as stated by Mayr (Ref 3), tend to be kept as confidential know-how.

More recently, an additional variable was observed; i.e., the mold shape related to heat treatment distortion. It was reported that heat treatment distortion in case carburized crown wheels can be related to the mold or the as-cast shape. It was postulated that a round mold (with better conformance to the shape of the heat treated product) would result in less distortion than square or rectangular molds (Ref 4).

A similar test was reported elsewhere on carburized press quenched crown wheels (Ref 5) produced from 385 × 265 mm and 140 mm diam continuously cast materials. This investigation proved that the as-cast shape has a measurable and dominating influence on the distortion in the carburized components in the quenched and tempered condition.

For obvious reasons, the positive influence of the round as-cast shape upon distortion stimulated interest both from the steel makers and users. A joint project was initiated with Volvo (Gothenburg and Koping, Sweden), UES Steels (Stocksbridge, UK), Ovako (Hofors, Sweden), and SKF (Schweinfurt, Germany) in order to investigate the reported effects for high volume steel production and series production of case carburized clutch sleeves, gears, and bearings. The results of these investigations are summarized in this report.

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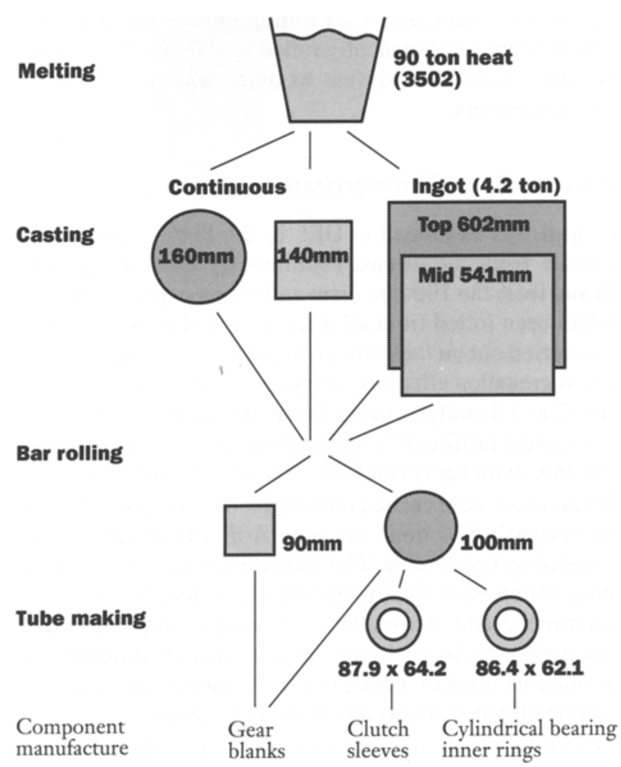


Fig. 1 Case carburizing steel manufacturing route

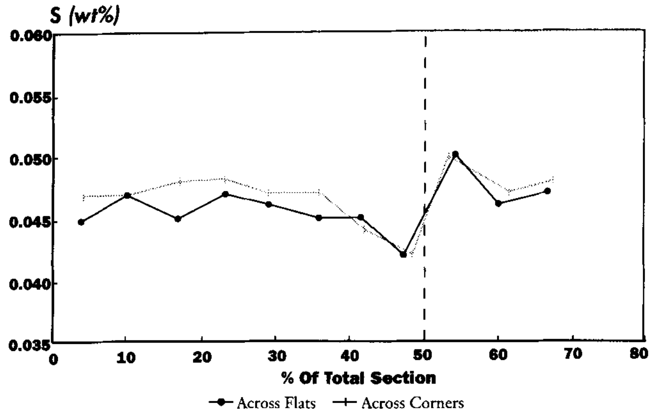


Fig. 2 Sulfur segregation profile; 140 mm square rolled to 100 mm diam

2. Test Materials

2.1 *General*

In order to evaluate the mold shape and distortion relationship, an extensive test program was performed in the participating companies. The materials were produced from both the continuous casting and ingot casting routes. The composition of the case carburizing steel approximated that of grade SAE 3120. See Table 1 for details of the test steel composition.

Figure 1 provides a schematic diagram of the manufacturing routes. The steel was produced at UES as a single 90 t heat, which was cast in three forms: continuously cast 140 mm square, 160 mm diam, and 4.2 t rolling ingots. These as-cast products were then subsequently rolled to 100 mm diam round and 90 mm square. Conversion to tubes was carried out at Ovako Steel, Hofors.

2.2 *Bars and Tube Characterization*

The heat was examined at UES in the form of transverse slices taken from the as-cast continuously cast squares and rounds and from the 100 mm diam and 90 mm square sections, which had been rolled from all three as-cast shapes. Hot etching was carried out on these slices, and an attempt was made to quantify segregation effects by carrying out edge to center traverses for C and S analysis using 5 mm diam drillings. Figure 2 shows a typical profile of S segregation, assessed by drillings on a 100 mm diam bar rolled from concast 140 mm square.

The traverses were carried out in both the "across flats" and "across corners" directions, remnant from the as-cast square and revealed by hot etching. This method was not successful in revealing differences in segregation characteristics between "across corners" and "across flats" on any of the sections. However, the ability to discern remnant square as-cast structures on rolled round sections by hot etching showed that, as expected, segregation effects were present at the billet stage.

Hot etching of the tube sections gave macroetch patterns that made it possible to visually recognize the round, square, and ingot shapes. See Fig. 3.

Table 1 Composition of the test steel SAE 3120 type

Element	Heat No. 3502 Composition, wt%
C	0.185
Si	0.30
Mn	0.95
P	0.018
S	0.049
Cr	0.97
Mo	0.11
Ni	1.19
Cu	0.19
Sn	0.014
Al	0.021

3. Distortion Tests and Results

3.1 *Gear Blanks*

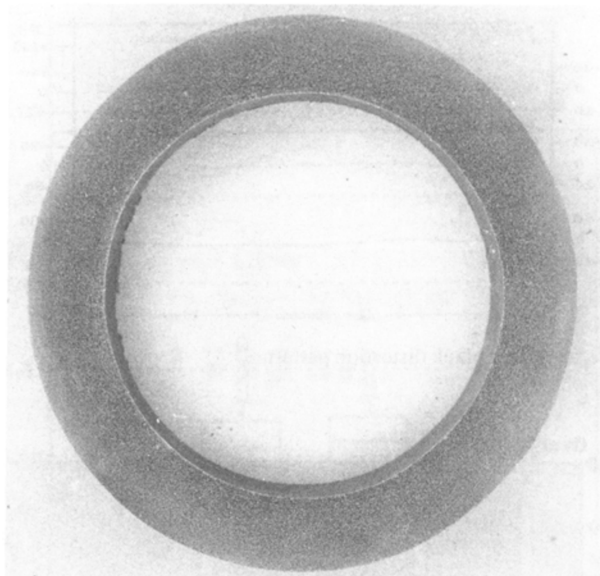
Six variants of the case carburizing steel were investigated by UES. The variants originated from the 140 mm square and 160 mm round continuously cast and the ingot cast material with all the materials being rolled to 100 mm diam or 90 mm square bar. This gave six batches of material, identified as follows:

- SR—140 mm concast square rolled to 100 mm diam round
- RR—160 mm concast round rolled to 100 mm diam round
- IR—square 4.2 t ingot rolled to 100 mm diam round
- SS—140 mm concast square rolled to 90 mm square
- RS—160 mm concast round rolled to 90 mm square
- IS—square 4.2 t ingot rolled to 90 mm square

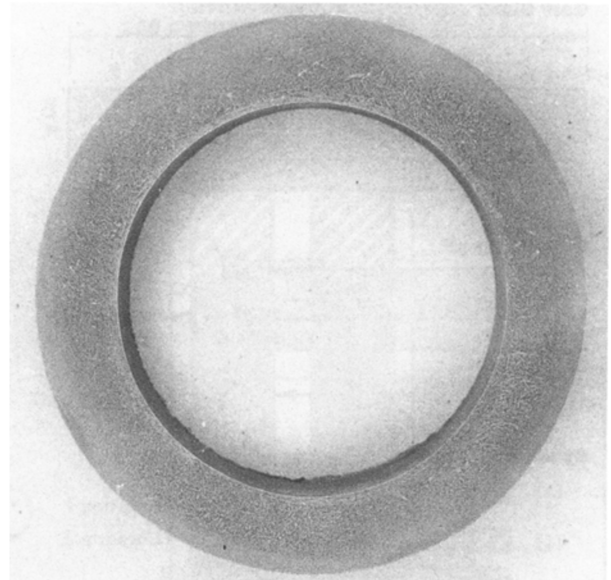
From each size variant, approximately 30 gear forging blanks were produced at the River Don Stampings Company, Sheffield, UK. See Fig. 4 for the dimensions of the component.

The next stages were carried out in conjunction with the Design Unit at Newcastle University, UK: (1) anneal; (2) machine reference surface; (3) measure dimensions A, B, and C, as shown in Fig. 4; (4) "blind" carburize heat treat with direct quenching without fixture, 910 °C for 7 h, 860 °C for 1.5 h, oil quench 150 °C for 6 min, cool to room temperature, wash, temper 150 °C for 2 h; (5) lightly sand blast; and (6) remeasure dimensions with Fourier analysis.

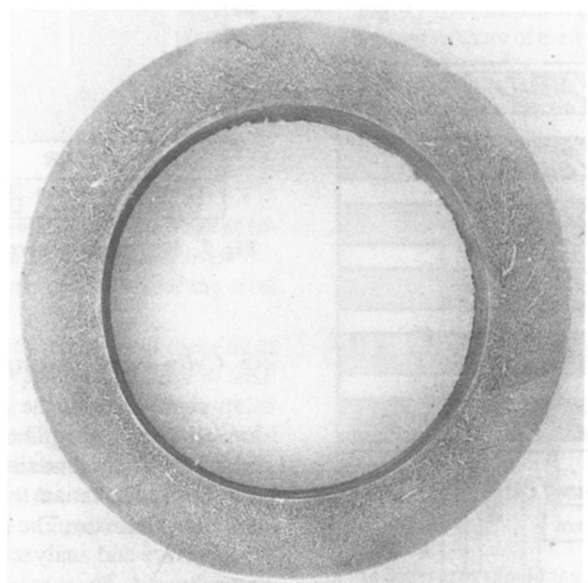
Figure 5 shows a plot of a typical circumferential distortion pattern on dimensions A, B, and C after heat treatment. Any influence of as-cast or rolled shape upon distortion behavior would have been revealed in the circumferential measurements around dimension B. Figure 6 shows the contribution to out-of-round (OOR) at each of the Fourier harmonics. The only significant contribution is from H2, corresponding to ovality, and as-cast and rolled shape have no significant effect upon this distribution. Ovality, defined by the largest diameter less the smallest, had mean values of 50.4 to 68 μm and standard deviations of 33.6 to 46.8 μm for dimension B as plotted in Fig. 7. As-cast and rolled shape had no discernible effect upon the magnitude of this ovality. Measurements across the flange section in the axial direction, dimensions A and C, showed a wave



Ingot middle



140 mm square concast



160 mm diameter concast

Fig. 3 Tube macroetch patterns

pattern of distortion, which also could not be related to as-cast or rolled shape.

3.2 *Clutch Sleeves*

The four tube blank variants, as shown in Fig. 1, were manufactured into clutch sleeves and tested by Volvo, Köping. The tests on each variant involved 256 clutch sleeve components with the following manufacturing and test sequence being followed: (1) turning; (2) broaching; (3) marking of test rings; (4) measuring; (5) loading on trays; (6) case carburizing in pusher furnace, 800 °C for 6 h; (7) 0.6 mm effective case depth; (8) direct quenching in oil; (9) tempering 150 °C for 2 h; and (10) remeasuring.

The space width of all of the clutch sleeves was measured with a spline comparator. The minimum space width, the functional requirement of the clutch sleeves, correlated well with ovality.

Measurements showed that the rings exhibited some ovality after machining. After carburizing and hardening, the same

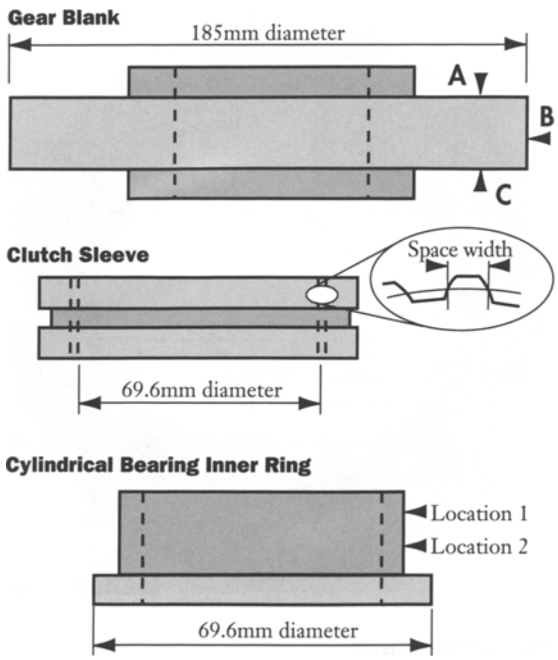


Fig. 4 Distortion test components

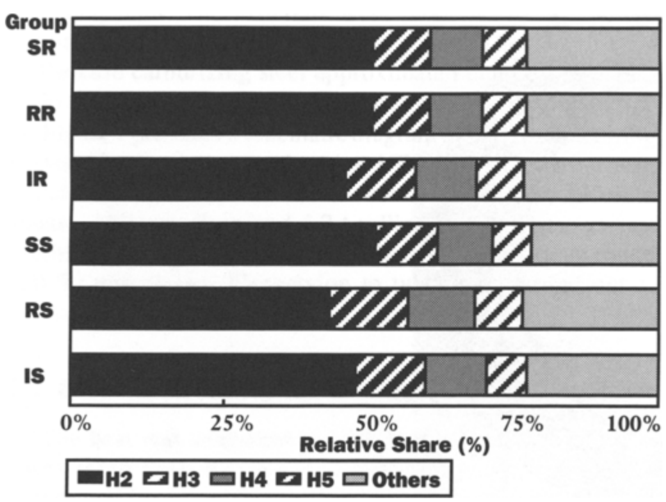


Fig. 6 OOR in forged and heat treated gear blanks expressed as share of harmonics

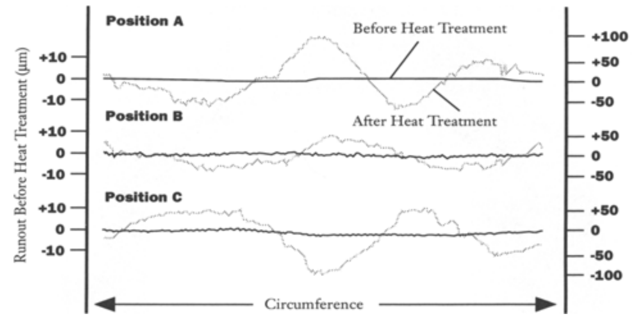


Fig. 5 Gear blank distortion patterns

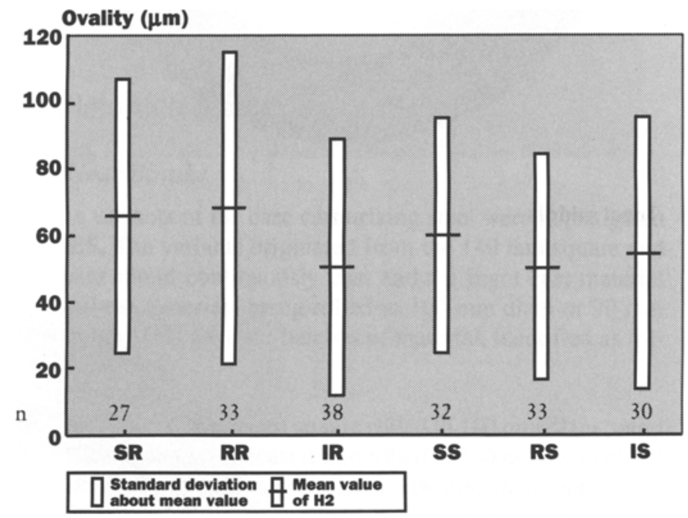


Fig. 7 Forged and heat treated gear blanks; values of ovality

form of ovality was maintained in the majority of sleeves, and no correlation in the magnitude of distortion with cast shape was observed. Figure 8 shows that the distribution of minimum space width after case hardening was approximately similar for the four variants. About 80% of the values are within 0.02 mm. It was therefore concluded that the as-cast shape did not influence distortion of clutch sleeves in these experiments.

Some extreme values of space width were observed and are plotted in Fig. 8. They are probably related to nonoptimized stacking during heat treatment. If any influence of the as-cast shape upon distortion of clutch sleeves exists, then it is insignificant as compared to the other influencing factors.

3.3 *Cylindrical Bearing Rings*

In common with the previously described tests on clutch sleeves, the cylindrical bearing inner ring tests were performed on all four case carburizing steel tube variants. See Fig. 1. Fifty rings from each variant were produced in the SKF Schweinfurt factory in Germany. The measurements were made on a measuring device and analyzer, Type MWA 160, produced by SKF Steyr, Austria. The measurements were carried out in two locations as shown in Fig. 4. The following manufacturing sequence was applied: (1) turning in 6 spindle automatic lathe; (2) marking rings in bore; (3) measuring rings, at locations 1 and 2; (4) positioning marked rings on heat treatment tray; (5) loading one ring per tray layer and three trays stacked on each other; (6) carburizing in pusher furnace 920 to 940 °C (1.2 mm effective case depth), equalizing 835 °C; (7) direct quenching on lowering platform in oil at 90 °C; (8) tempering 160 °C for 2 h; and (9) remeasuring and performing Fourier analysis.

Fourier analysis of the measurements was carried out. Figure 9 shows Fourier harmonic shares for the rings. The second order harmonic (H2) takes about 70% of the total. This harmonic represents ovality; thus ovality is evidently the main factor in the ring OOR. The amount of ovality is quantified by the amplitude of the second order harmonic, and the relative amplitudes are given as bar plots in Fig. 10. This figure shows the

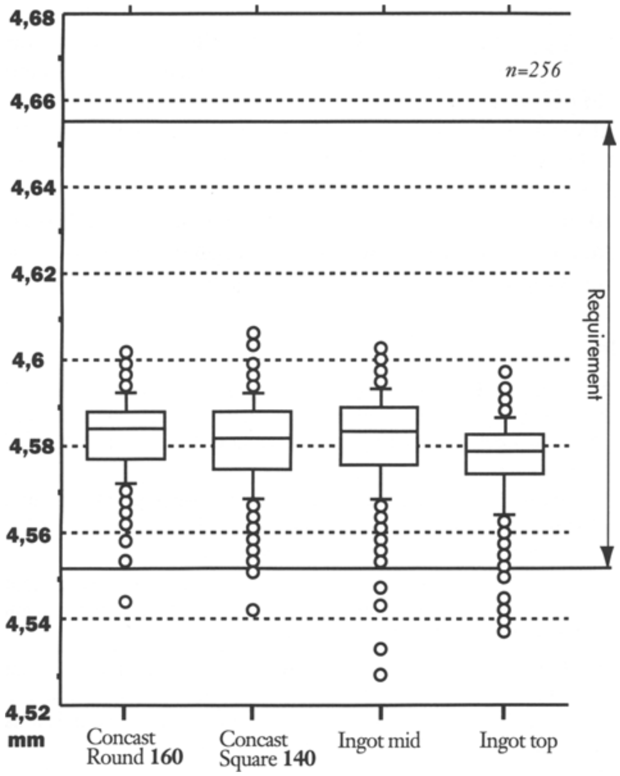


Fig. 8 Case hardened clutch sleeves; box plot of minimum space width

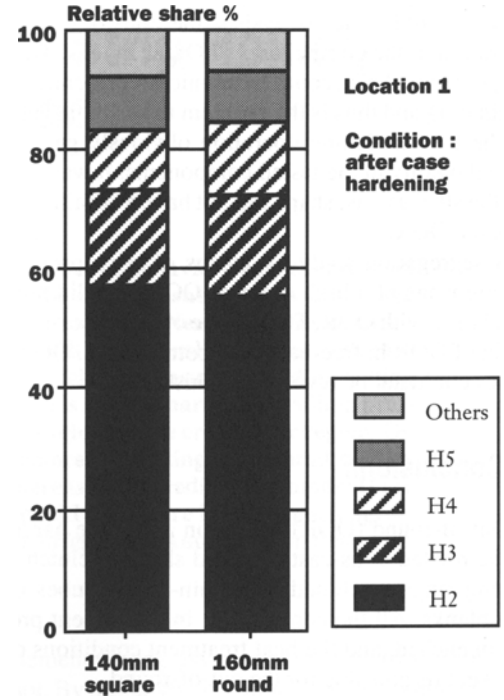


Fig. 9 Case hardened cylindrical bearing rings; OOR expressed as share of harmonics

relative mean values and standard deviations of 50 rings at locations 1 and 2, after machining and after case hardening.

Clearly, no influence of the original cast shape of the steel was observed in this investigation.

Distortion extremes were observed, and some of these rings were subjected to detailed metallographic evaluation at SKF ERC and at Ovako Steel with respect to elemental segregation effects. By use of programmable scanning electron microprobe analysis techniques, the cylindrical bearing inner ring cross-sections were analyzed at SKF ERC with a radial lateral resolution of 250 μm and a relative chromium content analysis precision of ±10%.

The tests showed that micro, or short range, chromium segregation did exist in the rings. However, no systematic correlation was observed between the macro, or long range, segregation and the degree of out-of-roundness.

Ovako Steel carried out a microprobe analysis on further elements and reached a similar conclusion.

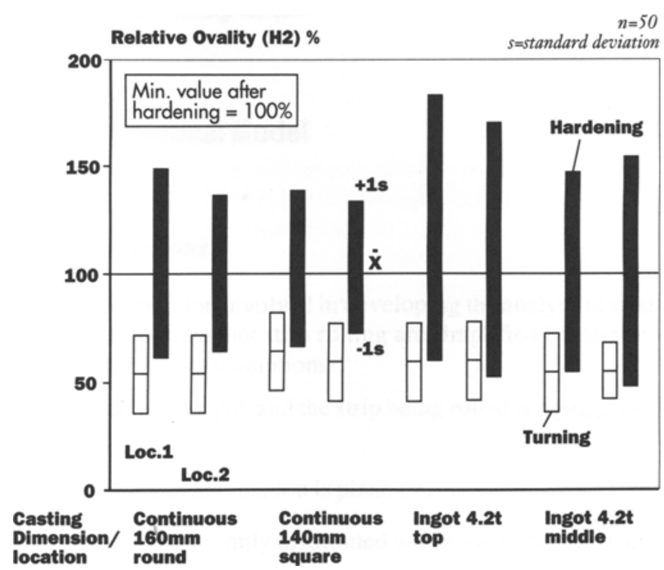


Fig. 10 Case hardened cylindrical bearing rings; relative ovality (harmonic 2) related to as-cast shape

4. Discussion

Recently, the influence of the as-cast shape of the steel was shown to have a dominant influence in some specific cases of fixture quenched, case-hardened components. The present study was devised to test the influence of this parameter on the distortion of some typical free-hardened components in general use: bearing rings and clutch sleeves. In addition, a gear blank was included in the study.

A unique split-melt technique was used to acquire the same case hardening steel in different cast shapes: round and square continuous cast and ingot. All steel variants and hardening operations met the relevant specifications. An extensive mapping of segregation was performed, and the steels all showed normal segregation patterns.

The use of Fourier analysis in the study of OOR enabled the separation of the components of OOR. In these free-quenched components, the second harmonic, representing ovality, is dominating and thus is the problem to be studied at first hand.

The free-hardening operation obviously gave rise to substantial ovality in the tested components. It was clearly shown that the steel as-cast shape did not have a dominating influence upon the OOR.

A segregation study by means of microprobe analysis of bearing rings of a high order of OOR also did not reveal any correlation with OOR. Thus, some other cause or causes are the origin of OOR in free-hardened components. Obviously, these causes could not be revealed by this study.

5. Conclusions

Out-of-round (OOR) distortion after case hardening could not be related to as-cast or rolled shape in clutch sleeves and bearing rings machined from thin-walled tubes or in forged gear blanks. All the components in the present program were free quenched, and the heat treatment conditions or other factors were responsible for the out-of-round.

Acknowledgments

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