GAS CARBURIZING VS. CONTOUR INDUCTION HARDENING IN BEVEL GEARS

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The following Boeing study compares distortion of AGMA quality class 10 bevel gears made of 9310 steel that have been gas carburized to those that have been contour induction hardened.

This paper examines the impact on distortion of two processes using traditional gear measurement techniques. It will discuss design considerations involved with switching from gas carburizing to contour induction. Core property considerations will be reviewed, and the impact of a conversion from gas carburize to contour induction in terms of production flow and cost will be discussed.

SUMMARY

The aircraft industry is facing some of the most difficult financial challenges in the history of aviation. Much work has been put into cost reduction efforts in the last few years. The authors were members of a team within Boeing Commercial Airplanes that were able to show a significant cost reduction for the manufacture of straight bevel gears without sacrificing design requirements. A review of the manufacturing methods for straight bevel gears indicated that significant cost was associated with the carburizing process. These costs included touch time, process time and cost, and unacceptable scrap rates.

OVERVIEW OF THE 3633 STRAIGHT BEVEL GEAR

The 3633 straight bevel gear is used in the trailing edge flap drive system of the 737. The 3633 gear is used in the angle gearbox noted in fig. 1. The gear has a shaft angle of about 162 degrees and a diametral pitch of 8.5 (2.99 module) and a Coniflex—trademark of The Gleason Works—tooth flank. The gear is over hung mounted (outboard of the two shaft support bearings) in an aluminum gearbox and transmits about 40 Hp under maximum load. The drive system operates about eight times per flight with a total run time of about one minute in both the extend and retract directions with a variable opposing load in each direction. The gear is manufactured to approximately AGMA—the American Gear Manufacturers Association—Quality 10 tolerances. The gear is case carburized 9310 steel per AMS 6265 and heat treated to a 36-41 HRC core hardness. Case is 58 HRC minimum, with a depth of 0.64mm to 0.90mm.

Straight bevel gears have been traditionally used on large transport aircraft because they can be manufactured in one piece for straddle-mounted applications (gear mounted between bearings). This affords a significant weight savings over multi-piece spiral or Zerol—trademark Gleason—bevel gear straddle mounted designs. Non-straddle mounted applications, such as the 3633 gear, continue to use straight bevel gears for reasons of machine tool commonality.

DESIGN CONSIDERATIONS

Contact Pattern

The performance of bevel gears is significantly influenced by the relative contact between mating gear pairs. This relative contact is represented by the contact pattern or bearing, which is simply the wear pattern left on each of the two gears when coated with a marking compound, then run together under load in a bevel gear tester. Figure 2 shows a typical contact pattern of a bevel gear similar to the 3633 gear. A good contact pattern runs from the heel to the toe of the flank of the tooth and from nearly the root to the tip under maximum operating load. In general, a good contact pattern does not "run off" the edge of the tooth in any direction under any expected load. (There are exceptions, but they are out of the scope of this paper.) Gears with poor contact patterns are noisy and subject to dynamic loads and vibrations. Poor contact patterns also tend to cause unwanted load concentrations, which in turn may overload portions of the tooth leading to durability failures, premature wear, and/or edge chipping. Close control of the contact pattern also allows parts to be interchangeable rather than manufactured as matched sets, which allows reduced inventory costs.

"Perfectly" machined straight bevel gear teeth would exhibit end loading distress in much the same way a cylindrical roller would under high load. And, like cylindrical rollers, straight bevel gear teeth are machined with a crowned lead, or Coniflex along the length of the tooth. The total amount of Coniflex machined into a tooth varies with the operating requirements and the physical and metallurgical properties of the gear, but usually amount to only a few hundredths of a millimeter. Control of the amount and location of the Coniflex is critical to achieving an acceptable contact pattern.

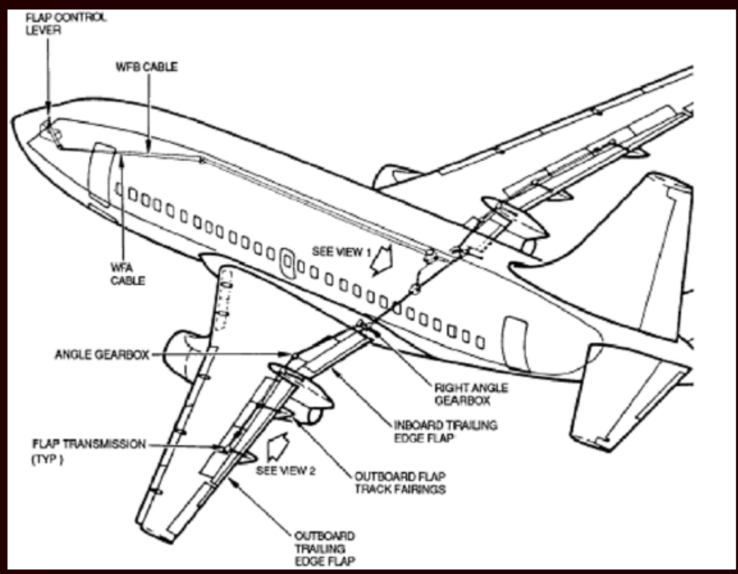

Fig. 1: Schematic of the 737 flap drive system.

Unfortunately, unlike other bevel gear forms, straight bevel gears cannot be economically ground after heat treatment in order to correct distortion because the Coniflex tooth form is incompatible with the kinematics required for grinding. The gear teeth must therefore be cut to anticipate the expected distortion during heat treatment in order to meet the final tolerance requirements.

Case Considerations

Case carburizing and heat treatment was originally selected for the 3633 bevel gear to ensure maximum wear and pitting resistance of the gear tooth while maintaining the maximum possible ductile core for bending strength and impact resistance. The carburized case depth was selected to ensure that the material strength exceeded the expected subsurface shear stress associated with surface contact throughout the duty cycle. The same criteria must be applied to selecting an induction hardened case depth.

Carburizing a gear tooth results in two distinct types of distortion. The first is the local distortion of the profile of the tooth from the desired theoretical form, both along the profile and along the lead. This distortion comes from both the diffusion of carbon into the surface and changes to the microstructure due to heat treatment. Both of these mechanisms change the local volume of the case, resulting in residual stresses and associated material strain. The second type of distortion results from the gear blank itself, where different parts of the gear react to the heat treatment differently. Influencing factors include metallurgical factors (local carbon content, impurities, existing inclusions, the presence of pre-existing residual stresses), variations in the thermal process (location in the oven, evenness of heating and cooling, quench rates) and geometrical considerations (size and shape of the part). This distortion tends to cause the pitch cone to "potato chip" (local and global variations in the pitch cone angle). Both types of distortion have detrimental effects on the contact pattern. Through hardening would have left the core too brittle. Through hardening may also require finish machining in the hardened condition.

Nitriding has not been popular for aircraft gears for a number of reasons. First, nitridable steel alloys tend to have lower core strengths and therefore represent a weight increase when compared with carburizing steels. Second, nitrided cases perform poorly near limit strength (where most aircraft bevel gears are designed), tending to crack and flake thus loosing the desired hardened surface and contaminating the gear box with hard particles. Third, nitriding tends to involve long processing times which impact costs. Fourth, while nitriding involves less distortion than carburizing, some distortion still takes place and would require similar efforts to control distortion during processing.

Strength Considerations

"Composite" (case hardened) metal parts tend to outperform homogenous (through hardened) metal parts in bending strength in that they benefit from the increased outer fiber strength

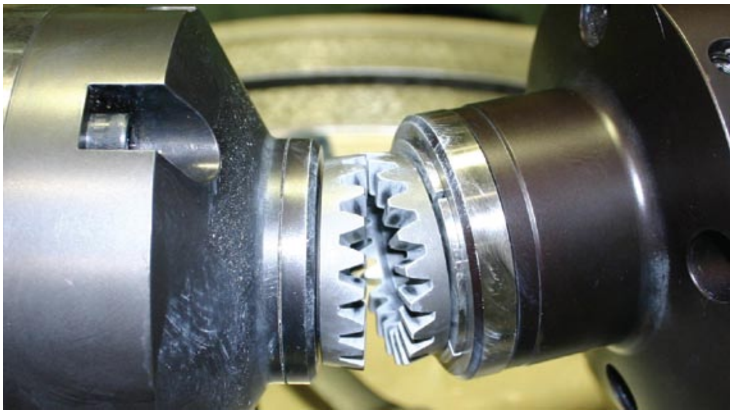

Fig. 2: Typical straight bevel gear contact pattern.

associated with case hardening. Carburized parts are significantly harder (and therefore stronger) than comparable induction hardened parts. In the design of large commercial air transports no credit is given to this additional capability for static strength (limit and ultimate) load conditions. It was therefore a simple matter of matching the core strength of both the carburized and induction hardened gears for this criteria. The fatigue criteria, however, does account for the additional strength of the case and must be considered carefully. Laboratory testing has confirmed that the fatigue strength of induction hardened gears is significantly less than a comparable carburized gear. The experimental procedures and results concerning the differences in fatigue properties of carburized gears compared to induction hardened gears are well documented in Reference 6. In this case static strength requirements and not fatigue drove the gear design.

Various low carbon steels are used for carburizing, and AMS6265 is often used in aerospace applications. When a part is carburized the alloy content is modified to provide case hardening. On the other hand, induction hardening a part modifies the surface heat treatment to provide case hardening. It is therefore important to select an alloy that meets performance requirements at both heat treatment levels for the induction hardening process.

Metallurgical Considerations

ANSI/AGMA 2001-D04 "Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth" (Reference 5), provides descriptions of the desired metallurgy of the case and core for both carburized and induction hardened gear teeth. The carburized 3633 gear meets or exceeds all metallurgical requirements of Table 9, Grade 3, in Reference 5. The carburization process is typical for aerospace applications: Carburization at 900C, cool to room temperature, austentise at 815C, oil quench, followed by -80C low temperature stabilization and 165C temper. Figure 3 is a micrograph of a carburized tooth near the heel of the tooth.

The induction 3633 gear meets or exceeds the requirements of Table 8, Grade 2, of Reference 5. The induction 3633 gear also meets or exceeds the applicable requirements of Table 9, Grade 3, of Reference 5. While metallurgical properties for carburized gears of this type are well established, induction metallurgical characteristics are less well known. The Grade 2 description does not adequately describe the metallurgy. In this example AMS6414 (4340) material was first heat treated to a core property of 34 to 40 HRC. An induction case was applied followed by a 165C temper for a 56HRC minimum case hardness. The induction case to core transition is very short, typically 0.03mm. The induction case consists of fine tempered Martinsite. The induction case is often not as uniform as a carburize case. Figure 4 is a micrograph of an induction hardened tooth near the heel of the tooth. Consideration of this condition must be given when deciding on case depth requirements. Case depth requirements should be specified for the root and tip separately. In

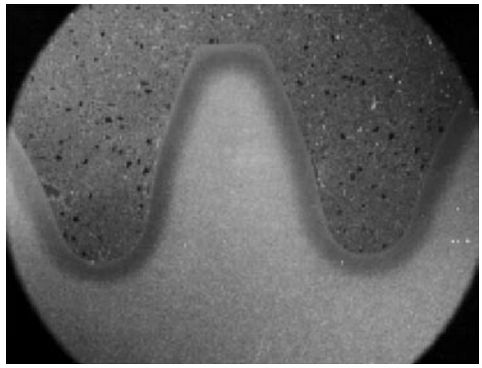

Fig. 3: Representative carburize tooth cross section, 5X.

this example the case depth of the induction root was less than the carburize root and the induction tip was greater than the carburize tip.

PROCESSES

Carburize

Carburizing is a historic process that remains in wide use for case hardening gears. While there are multiple methods for carburizing, gas carburizing is the most common and is discussed in this paper. The steps to carburizing can be

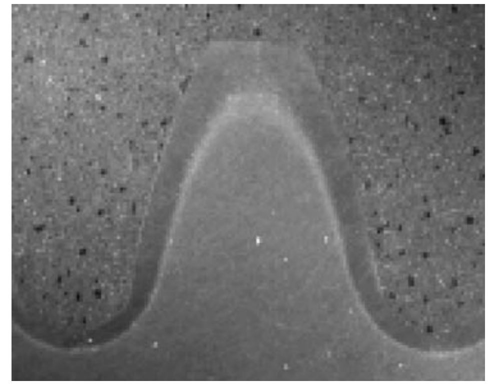

Fig. 4: Representative induction tooth cross section, 5X.

grouped into three major steps: 1) pre-processing; 2) processing, and; 3) post-processing. Much of the cost associated with gas carburizing is a result of pre- and post-processing. Pre-processing consists of:

- Adjustments to the gear generation process to compensate for carburized distortion. The objective is to distort the gear tooth geometry, such that after carburizing the gear has the desired geometry. Development of the adjustments includes application of prior experience and trial and error. In the case of the example gear, an offset is dialed into the V and H axis of the bevel gear test machine. Adjustments to the gear generator are made such that the final desired pattern is generated with this offset. The offset represents the warpage of the carburize process.

- Masking and stop off. In many applications it is undesirable to carburize the entire surface of the part. Often only the gear teeth working surface is to be carburized. To accomplish this selective carburization, it is necessary to mask the areas that are not to be carburized with a stop-off coating or copper plate. After carburizing, the stop-off coating or copper plate is removed. There can be 20 minutes of touch time per piece for application and removal of masking. The use of copper plating also involves the use of hazardous materials, including arsenic.

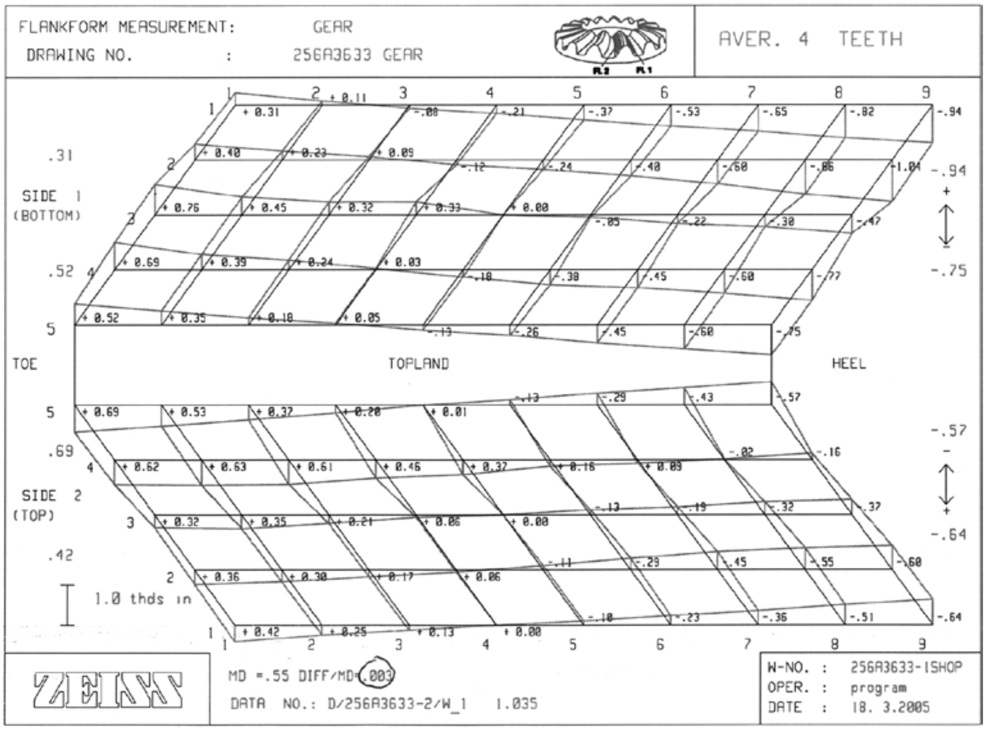

Fig. 5: Gear tooth profile prior to carburizing.

Processing Carburizing: Time, temperature, and carbon potential relationship to case depth are well established. One of the advantages of case hardening with gas carburizing is the fact that little if any development is needed to establish required case properties. However, the racking technique in the carburizing furnace may require development. For some applications the development of quench fixtures and other tools may be required. Parts are placed in a furnace heated to the carburizing temperature for the required time. After carburization, the parts are either direct quenched or cooled to room temperature, and subsequently heat treated. The later method produces a more stable metallurgy.

Post-processing: After carburization parts are cleaned and the stop-off coating—e.g. copper plate—is removed. After final machining, the contact patterns are checked with a predetermined load and zero offset of the V and H axis on a suitable gear-testing machine. At this point the gears are either good or scrap. The amount of labor involved in carburizing is clearly substantial.

Induction

Pre-processing: Essentially no pre-processing is required. The induction process has been found to cause minimal geometry changes. As a result there is no requirement to make pre-heat treatment adjustments to the gear tooth

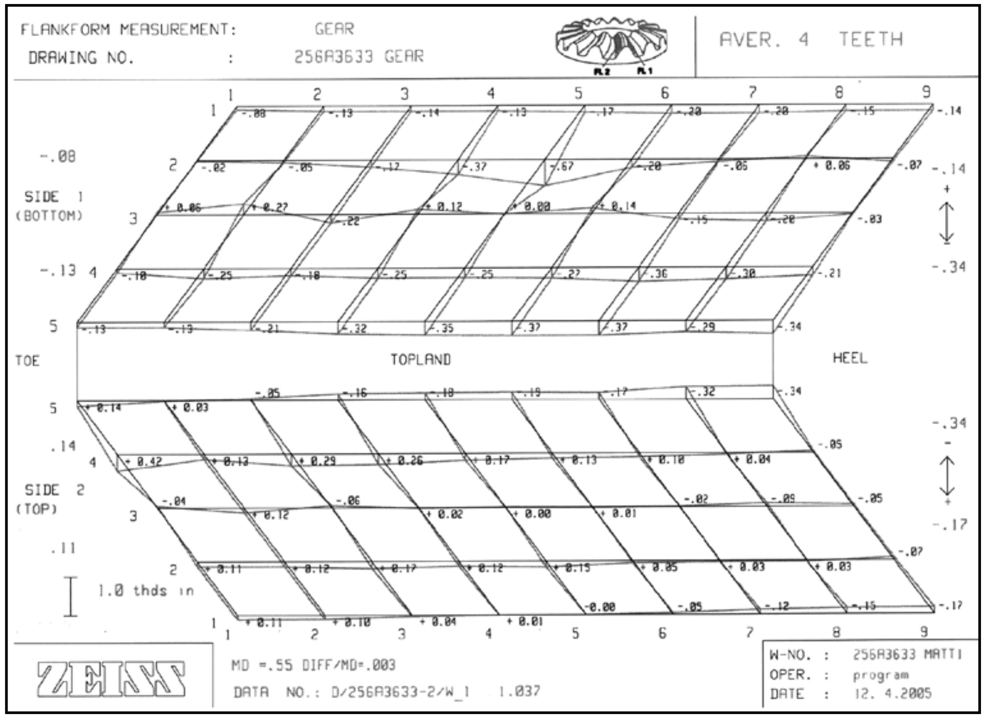

Fig. 6: Gear tooth profile prior to induction hardening.

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geometry to achieve the desired contact pattern. With induction the case hardening pattern is controlled by tooling such as the induction coil and the power-frequency-time parameters of the induction process. There is no need for stop-off coatings such as copper plate.

Processing: The induction hardening process can take significant development effort. Coil design and power parameters can take many iterations to obtain a satisfactory case. With modern computer controlled workstations, setting up and running an induction job is rather simple. The coil/s are placed on the workstation, workpiece holder put in place, and finally the workpiece. The recipe for time and power developed prior is executed. In seconds the case hardening operation is complete. Furnace or induction temper follows. During induction process development critical parameters are established. For gears like that of this study an induction power supply capable of approximately 230 kHz and at least 400kW is necessary. In this specific example a power supply operating at two frequencies, (~10kHz & ~230kHz), was used with 105kWs applied.

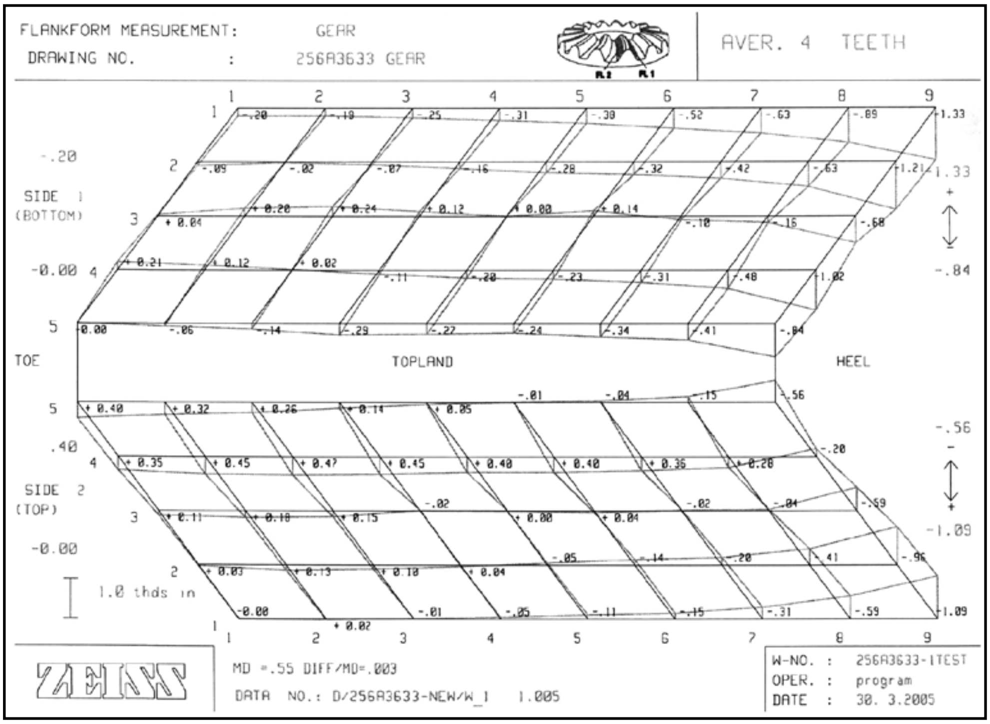

Fig. 7: Gear tooth profile after carburizing.

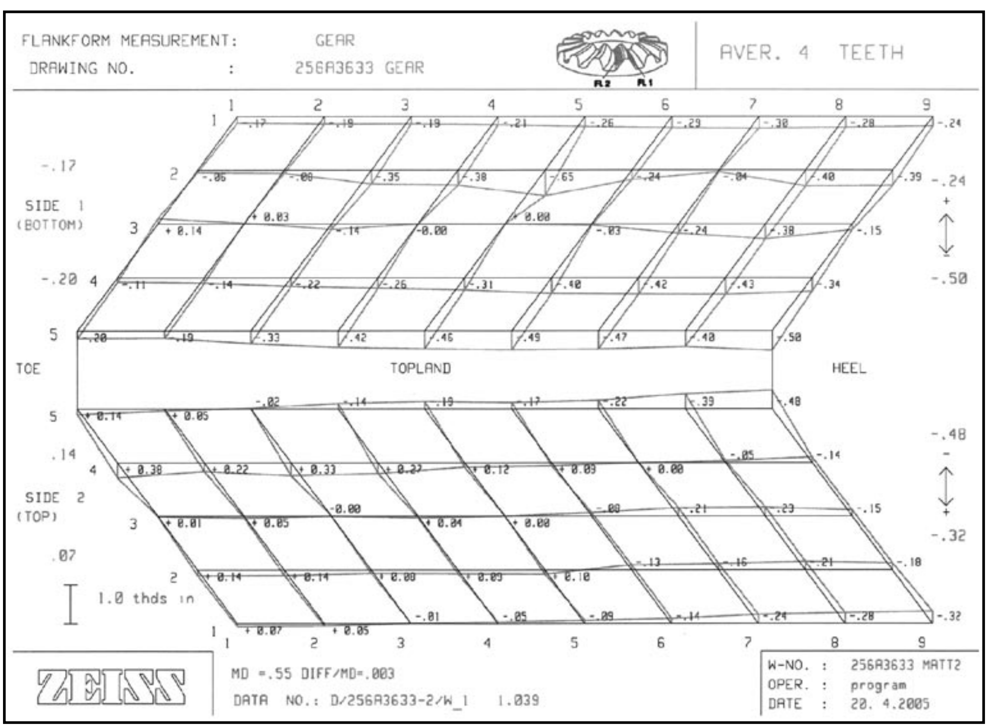

Fig. 8: Gear tooth profile after induction hardening.

Quenching: As with heating, quenching must be very repeatable and timed with the end of the quench cycle. Water-glycol spray quenching is the most effective for obtaining a quench that is fast enough without adding distortion.

Post Processing: Normal cleaning is used to remove residual quenchant. Parts are inspected for contact pattern.

Cost: The flow time of an induction hardened gear is typically 40 percent of the flow time for a carburized gear. This reduction is due to the simplified gear cutting setup, elimination of masking, distortion, and other problems.

Impact of Distortion

With most gear forms (spur, helical, spiral, etc.) distortion on the finished product is compensated for by grinding the gear to correct the final tooth geometry. Grind stock needs to be provided. Additional time and costs are incurred for the extra set up, grinding, and inspection steps. For straight bevel gears, post case-harden grinding is not a practical option. Excessive distortion in this situation is often cause for scraping the part. In those cases where the distortion is not excessive—i.e., is just within the acceptable tolerances—the assembly shop may attempt to adjust shims to meet the assembled contact pattern requirements and additional touch time is incurred.

COMPARISONS OF DISTORTIONS

Figure 2 shows the resulting contact pattern of a pair of bevel gears mounted in the gear tester. In this case the pattern was checked at full load. For carburized gears, the pre-carburize contact pattern is controlled by applying an offset to the gear tester. This amount is determined by experience. This technique will produce the desired pattern at zero offset after carburizing. Induction hardened gears are cut with no offset. The desired pattern is essentially the same pre- and post-hardening. **Continued on Pg. 54 >**

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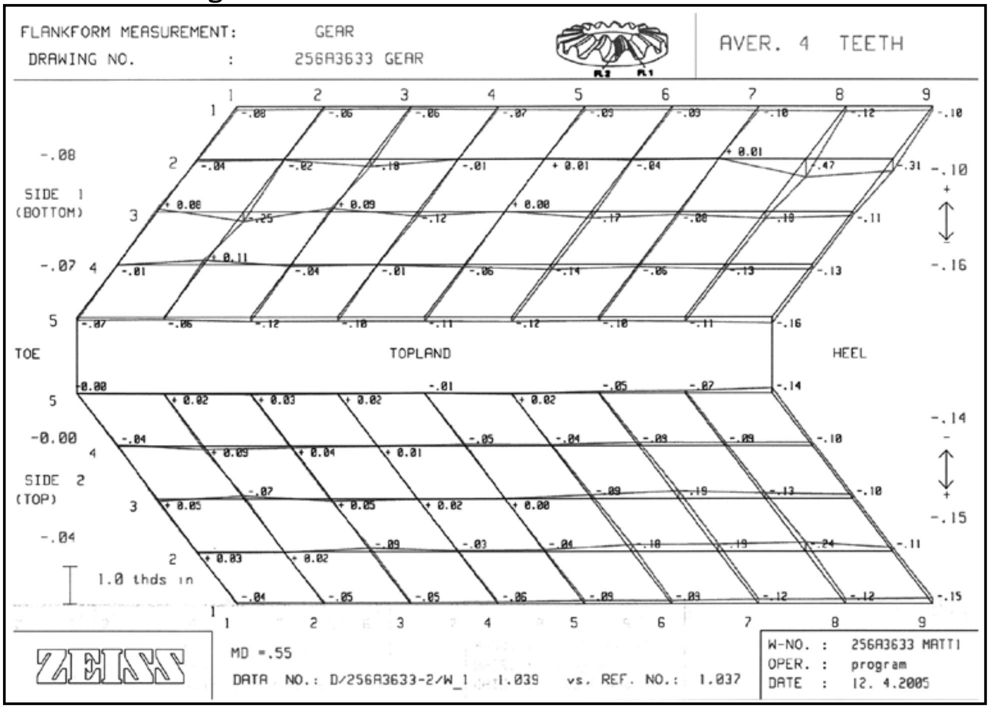

Fig. 9: **Arithmetic difference between the tooth profile of a "green" gear prior to induction hardening and a finished induction hardened gear.**

Figure 5 shows a profile plot of a gear prior to carburize. The darker lines represent the theoretically perfect Coniflex shape normalized to straight lines. The lighter lines represent the deviation of the actual tooth form from the theoretical shape. In this case it is expected that the heel will move in the plus direction and the toe will move in the minus direction. In addition, there is an expectation that the pressure angle will change during carburizing and heat treatment.

Figure 6 shows a gear generated for induction hardening. No intentional changes from nominal have been introduced to pre-compensate for distortion or warpage.

Figure 7 shows a gear profile after the carburizing process. Comparing it to fig. 2 shows how successful the pre-processing gear generation was in compensating for the changes that occur in the carburizing process. The toe of the tooth has indeed moved in the minus and the heel has moved plus. In addition some correction of the pressure angle is evident. Much of this profile movement can be attributed to changes in the pitch cone angle due to heat treat warpage. In this case there is still some drop off near the heel of the tooth but this could be judged acceptable for many applications. This ability to cut a "green" gear to compensate sufficiently for heat treat warpage and obtain AGMA Quality 10 final tolerances is considered state of the art.

Figure 8 shows a gear tooth profile after induction hardening. Variation from nominal is the result of normal machine variation and is expected and well within the tolerances for an AGMA quality 10 gear. This profile is essentially unchanged from the pre-induction hardened profile.

Figure 9 shows the difference between the measurements of figs. 6 and 8. For all practical purposes there is no change in the gear tooth geometry as a result of the induction case hardening process.

Induction Process Considerations

Induction case hardening requires several major components. An adequate power supply, workstation, induction coil/s, workpiece holding, and material handling are essential components. The power supply operating frequency, or frequencies, must be correct for the tooth size and desired case depth. The power supply must have adequate power to heat the case quickly enough to avoid significant conductive heat transfer to the core. This will not only deepen the case, but also temper back the core. Finally, the power supply must be highly repeatable. The workstation must accurately control the location of the gear. Induction coils need to be very well constructed. Dimensions and tolerances tightly controlled and checked before each use. Gear case hardening with induction requires discipline and attention to detail.

CONCLUSION

Based on this and other bevel gears we have evaluated, we have found that induction hardening allows much closer control of surface distortion (less distortion) than conventional carburizing but sacrifices some mechanical properties. In the case of straight bevel gear teeth, which are usually sized by static strength (for large commercial transports), this loss of mechanical properties is acceptable.

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