

Gear Heat Treatment Selection with a Duty Test Matrix

A practical framework for matching requirements to process routes and proof tests

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Heat treatment decisions for gears are often reduced to a surface hardness number. That shortcut can work for mild duty, but it frequently breaks down when contact fatigue, scuffing risk, shock events, distortion limits, or finishing constraints become dominant. Many late-stage issues trace back to the same pattern: the duty case is incompletely defined, the process window is underestimated, or verification confirms “a number” without proving the full property profile.

This article offers two practical tools for cross-functional reviews and early process alignment. Table 1 links common duty drivers to a shortlist of heat treatment routes, helping teams narrow options quickly and consistently. Table 2 maps each route to a minimum proof-test plan—case/layer depth, hardness gradients, microstructure confirmation, geometry stability checks, and surface integrity checks when hard finishing is involved. Used together, these matrices connect design intent to measurable evidence and inspection gates, reducing rework and late-stage surprises.



Figure 1—Heat treatment builds durable gear surfaces. (All images: PairGears)

Define the Duty Case First

You do not need a perfect model to make a better selection. You need a shared duty description that captures the dominant drivers.

Duty Inputs Checklist:

- Torque level: average and peak
- Shock severity: none / occasional / frequent (include reversals)
- Speed regime: low-speed high-torque vs high-speed sensitivity to small deviations

- Operating temperature: typical and peak
- Lubrication regime: full-film vs mixed/boundary; supply method
- Cleanliness risk: filtration level and ingress risk
- Life target: hours/cycles/warranty profile
- Distortion tolerance: runout/tooth deviation/fit-critical dimensions
- Finishing plan: grinding/honing/superfinishing available? stock allowance?

A practical method is to label each as Low/Medium/High, then pick the top two or three “non-negotiable” drivers. Those drivers determine the route shortlist.

Heat Treatment Routes: Strengths and Limitations

This section summarizes common routes used in gear manufacturing. The focus is not on marketing claims, but on what each route tends to deliver and what must be proven.

Induction (Surface) Hardening

Best at: Localized hard surface with a tougher core; efficient flow for many parts; can support distortion control when implemented well.

Where it fits: Moderate to high duty parts where selective hardening is practical and cycle time matters.

Limitations: Pattern coverage and uniformity; tooth-to-tooth variation; setup drift (coil path, scan strategy, quench stability).

Verification emphasis: Hardness mapping and depth checks at the highest-stress regions; distortion checks before/after finishing.

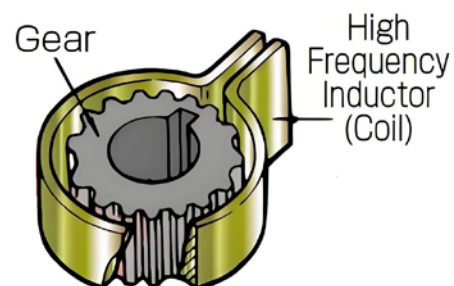


Figure 2—Induction hardens teeth fast with a coil.

Carburizing + Quench + Temper (Case Hardening)

Best at: Strong contact fatigue resistance with a tough core when case depth and gradient match the stress field.

Where it fits: High load, long life, and demanding durability requirements.

Limitations: Distortion scatter; coordination with finishing (stock, correction capacity, and surface integrity risk).

Verification emphasis: Effective case depth and hardness traverse, microstructure confirmation, core hardness, distortion statistics across loads; surface integrity checks after hard finishing when risk is elevated.

Nitriding

Best at: Hard surface with minimal distortion due to lower temperature; attractive for distortion-sensitive components.

Where it fits: Precision gears or parts where dimensional stability is the dominant constraint; wear/scuffing risk control in certain duty profiles.

Limitations: Typically thinner hardened layer; layer and compound-zone control; core must already be sufficiently strong.

Verification emphasis: Layer depth, near-surface hardness (often HV-based), microstructure/layer characterization, geometry checks pre/post.



Figure 3—Nitriding gives the shaft a hard, stable layer.

Through-Hardening (Quench & Temper, Q&T)

Best at: Economical route for bulk strength; robust process flow for modest-duty gears.

Where it fits: Lower contact stress designs, auxiliary gears, and applications where a deep hardened case is not required.

Limitations: Limited surface contact fatigue and wear resistance versus case-hardening routes; higher sensitivity to lubrication regime.

Verification emphasis: Bulk hardness and microstructure, geometry stability, surface finish compliance.

Normalizing (Primarily a Pretreatment)

Best at: Stress relief and microstructure refinement to support machinability and consistent downstream response.

Where it fits: Pretreatment to stabilize machining and reduce variability prior to hardening processes.

Limitations: Normalized properties alone rarely meet higher-duty requirements unless followed by hardening.

Verification emphasis: Hardness range, microstructure consistency, dimensional stability before next steps.

Route Selection Matrix (Duty Drivers → Route Choice)

The fastest way to shortlist routes is to identify the dominant duty drivers. Use Table 1 to narrow options, then confirm geometry/process compatibility and build the proof-test plan.

| Dominant Driver / Constraint | Induction | Carburize + Quench | Nitriding | Q&T | Normalizing |
|---|-----------|----------------------|-----------|-----|-------------|
| High contact stress, long life (pitting resistance) | C | R | C | A | A |
| High shock / bending-root robustness | C | R | C | C | A |
| High-speed sensitivity to small deviations | C | C→R (with finishing) | R | C | A |
| High scuffing risk (boundary lubrication events) | C | C | R | A | A |
| Distortion-sensitive geometry / tight fit | R | C | R | R | C |
| Limited post-heat-treat finishing margin | C | A C | R | R | C |
| Selective hardening needed (local zones) | R | A | C | A | A |
| Short lead-time / flexible routing | R | C | C | R | C |

Table 1—Simplified route selection matrix. Legend: R = Recommended; C = Conditional; and A = Generally Avoid.

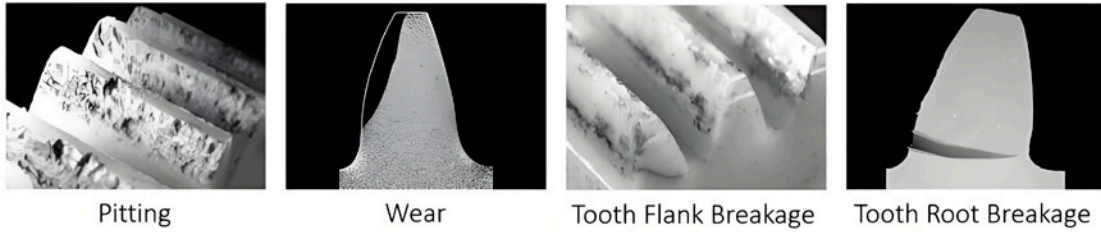
Verification Matrix (Route → Proof Tests)

Route selection should come with a verification plan that proves the assumptions the design relies on—especially for case-based routes.

| Route | Key Assumption to Prove | Typical Evidence Set (select per risk) |
|--------------------|---|---|
| Induction | Hardened pattern covers critical zones; uniformity is stable | hardness map; depth checks at critical sections; microstructure sampling; distortion/runout checks |
| Carburize + Quench | Case depth/gradient matches stress field; tough core; stable metallurgy | effective case depth; microhardness traverse; microstructure confirmation; core hardness; distortion scatter across furnace loads; post-finish surface integrity checks when needed |
| Nitriding | Layer is consistent; minimal distortion; core strength adequate | layer depth; near-surface hardness (HV); layer/microstructure characterization; geometry checks pre/post |
| Q&T | Bulk properties meet duty; contact stress is modest enough | bulk hardness; microstructure; geometry stability; surface finish verification |
| Normalizing | Stable microstructure and response downstream | hardness range; microstructure; dimensional stability before subsequent hardening |

Table 2—Verification Plan Matrix (Typical Minimum Evidence).

Traditional Failure Modes for Gears



Specific Failure Modes for Polymer Gears

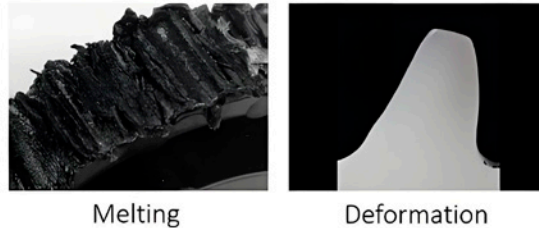


Figure 4—Typical gear damage patterns and failure appearances at a glance.

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Representative Duty Profiles

The same route can succeed or fail depending on which constraints dominate. The examples below illustrate how the matrix approach works.

Agricultural Machinery Drives

Typical traits: long service hours, contamination exposure, seasonal shock events, durability-first.

Route tendencies: carburizing for primary torque paths; induction for selective needs and robust cores where appropriate.

Proof-test focus: case-depth strategy or pattern coverage; distortion control plan; cleanliness and lubrication assumptions documented.

Heavy Truck Power Transmission

Typical traits: high torque, long mileage, repeated duty cycles, strict repeatability requirements.

Route tendencies: carburizing for high-load gears with hard finishing; nitriding for distortion-sensitive precision parts where the layer matches the duty case.

Proof-test focus: hardness traverse and depth evidence; distortion statistics; post-finish surface integrity risk control when grinding is aggressive.

Construction Equipment Reducers and Drives

Typical traits: transient peaks, shock loading, bidirectional events, rugged reliability.

Route tendencies: carburizing for heavily loaded stages; induction for large components and selective hardening cases; Q&T for modest-duty gears with appropriate design margins.

Proof-test focus: core robustness indicators, distortion gates, and documented acceptance criteria.

High-Speed Electric Drivetrains

Typical traits: high rpm and continuous duty where small geometry variation becomes more noticeable; stable finishing and distortion control are often decisive.

Route tendencies: carburizing paired with controlled finishing; nitriding where dimensional stability dominates and the layer fits the duty assumptions.

Proof-test focus: geometry stability pre/post, consistent finishing output, and verification that the achieved layer/case matches the design model.

Failure Modes and Evidence Chains (Fast Troubleshooting)

When a program experiences early failures or fit problems, the fastest path is symptom → evidence → correction.

Pitting / Spalling

- Symptom: pits growing into spalls on active flanks.
- Evidence: duty severity review; case depth/gradient vs stress region; surface condition and cleanliness.
- Corrections: revise duty assumptions; adjust case strategy or route; improve finishing/lubrication/cleanliness controls.

Scuffing (Adhesive Wear)

- Symptom: smeared or torn surfaces, rapid damage progression under boundary lubrication.
- Evidence: duty temperature and lubrication regime; surface condition; contact pattern and alignment checks.
- Corrections: raise scuffing margin via lubrication/cleanliness/finish strategy; reconsider route if scuffing is dominant.

Tooth Fracture

- Symptom: fracture often originating at root under shock.
- Evidence: shock classification; core microstructure/hardness; stress raisers and origin analysis.
- Corrections: ensure core robustness matches duty; stabilize process; adjust design margins or route as needed.

Fit or Assembly Problems After Heat Treat

- Symptom: parts do not assemble or require excessive correction.
- Evidence: geometry measurements pre/post; distortion scatter across loads; stock allowance vs correction capability.
- Corrections: distortion control plan, fixturing/quench strategy, gating inspections, and finishing alignment.

Distortion and Finishing: The Hidden Coupling

Even an appropriate route can fail without an aligned distortion and finishing plan.

Practical Actions

- Identify distortion-sensitive features early (runout, fit bores, tooth deviations).
- Define measurement gates: pre-HT baseline → post-HT → post-finish.
- Align stock allowance with realistic correction capability.
- Where hard grinding is used, include surface integrity risk controls appropriate to the process window.

Program Checklist

1. Capture duty drivers (shock, temperature, lubrication, cleanliness, life).
2. Select 2–3 non-negotiable drivers.
3. Shortlist routes using Table 1; eliminate A for non-negotiables.

4. Confirm geometry/process compatibility and finishing capacity.
5. Build proof tests using Table 2; prove case/layer assumptions.
6. Add distortion gates and acceptance limits.
7. If hard finishing is used, plan surface integrity risk controls.
8. Link failure modes to evidence chains before production ramp.
9. Lock process settings and traceability to reduce scatter.
10. Update matrices as capability data accumulates.

Conclusion

A robust gear heat treatment decision is not a single process choice. It is a matched set of duty assumptions, route capability, finishing constraints, and proof tests. The duty-to-route matrix helps shortlist workable options early, but the decision only becomes reliable when the verification plan proves the key assumptions with measurable evidence—such as case/layer depth, hardness gradients, microstructure confirmation, and post-heat-treat geometry stability.

Most late-stage surprises—premature surface distress, tooth fracture under shock, or fit and assembly issues—can be traced to an incomplete duty description, an underestimated distortion/finishing window, or verification that checks “a number” without confirming the full property profile.

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