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Comparative Analysis of the Effects of Carburizing, Plasma Nitriding and Nitrocarburizing on Performance Characteristics and Life Cycle of Automotive Components

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ABSTRACT
Automotive powertrain and chassis components operate under severe tribological and cyclic loading conditions. Surface engineering via thermo-chemical case hardening is therefore central to achieving high wear resistance, fatigue strength and durability while controlling cost and distortion. This review comparatively evaluates three widely adopted diffusion-based surface treatments—carburizing, plasma nitriding and nitrocarburizing—with a focus on their application to automotive components such as gears, shafts, cams, valves and brake discs. The paper discusses fundamental mechanisms, typical process windows, microstructure–property relationships and performance outcomes. Comparative data are synthesized for surface hardness, case depth, wear rate, fatigue life and corrosion resistance, along with their impact on life cycle and cost. Representative numerical values from recent experimental studies are organized in tables and conceptual plots to enable data-driven selection of the most appropriate process for a given component and loading condition.

Keywords: Carburizing; Plasma Nitriding; Nitrocarburizing; Case hardening; Automotive components; Fatigue life; Wear resistance; Surface engineering; Thermo-chemical treatments.

1. Introduction

Critical automotive components—transmission gears, camshafts, crankshafts, axle shafts, valve train parts and brake components—are simultaneously subjected to high contact stresses, sliding/rolling wear, impact and cyclic loading. To meet stringent durability, NVH and warranty targets while reducing weight, the outer surface must exhibit high hardness and compressive residual stresses, whereas the core must retain toughness and ductility. This performance gradient is most effectively achieved via diffusion-based case hardening processes rather than through-hardening.

Conventional carburizing is historically the dominant process for automotive gears and shafts, producing deep hardened cases (0.8–1.5 mm) with high surface hardness (≈58–64 HRC), enabling substantial improvement in rolling contact and bending fatigue life [1]. However, carburizing requires high austenitizing temperatures (≈900–960 °C) and subsequent quenching, which can cause distortion and necessitate costly post-machining.

Plasma (ion) nitriding and nitrocarburizing have gained prominence as lower-temperature alternatives, creating thinner but very hard compound and diffusion layers, often with minimal distortion and improved corrosion resistance. Plasma nitriding, typically at 450–580 °C in nitrogen/hydrogen gas mixtures, generates nitride phases and high compressive residual stresses that significantly enhance fatigue and wear resistance [2].Nitrocarburizing introduces both nitrogen and carbon into the ferritic steel matrix, forming ε-Fe_{2-3}(N,C) compound layers and diffusion zones with very good anti-scuffing and corrosion behaviour, particularly in ferritic nitrocarburizing (FNC) variants widely used for automotive brake discs, shock absorber rods and valve components.

The aim of this review is to:

Describe carburizing, plasma nitriding and nitrocarburizing from a process and microstructural perspective.

Summarize and compare typical process parameters relevant to automotive components.

Perform a comparative, data-driven assessment of their effects on performance characteristics (surface hardness, wear, fatigue, corrosion, distortion).

Assess their impact on life cycle and durability of automotive parts, including relative life extension and life-cycle cost implications.

2. Overview of Thermo-Chemical Case Hardening Methods

2.1 General Background

Case hardening by diffusion (carburizing, nitriding, nitrocarburizing, carbonitriding, boriding, etc.) modifies only the outer layer of a component, maintaining a tough core. Carbon, nitrogen and/or boron atoms diffuse into the surface at elevated temperature, forming hard phases (e.g., martensite, nitrides, carbonitrides, borides) that enhance surface hardness and fatigue resistance.

Three industrially dominant diffusion-based treatments for automotive steels are:

Carburizing (gas, vacuum, or plasma carburizing)

Plasma (ion) nitriding

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Nitrocarburizing (gas, salt bath or plasma; often ferritic)

2.2 High-Level Comparison of Methods

Table 1. Typical characteristics of carburizing, plasma nitriding and nitrocarburizing (literature-based ranges; representative, not absolute).

Attribute	Carburizing	Plasma Nitriding	Nitrocarburizing (FNC)
Typical temperature (°C)	900–960	450–580	500–580 (ferritic)
Atmosphere	C-rich gas or low-pressure C	$N_2 + H_2$ (often +Ar)	N- & C-bearing gas/salt (e.g. NH_3 + C)
Phase during treatment	Austenitic	Ferritic	Ferritic
Quench required	Yes (oil/gas)	No (usually)	No / mild
Typical case depth (mm)	0.8–1.5	0.2–0.7	0.1–0.5
Surface hardness	58–64 HRC	900–1200 HV	700–1100 HV
Distortion tendency	High	Low	Very low
Wear resistance	High	Very high	Very high
Fatigue strength (bending/contact)	High	Very high	High–very high (contact)
Corrosion resistance	Limited (unless coated)	Mildly improved (depending on steel)	Significantly improved (post-oxidized)
Typical parts	Gears, shafts, cams, rings	Gears, shafts, molds, dies, cam/followers	Brake discs, shock rods, pins, valves

3. Carburizing of Automotive Components

3.1 Process Description and Microstructure

Carburizing introduces carbon into low- or medium-carbon steels at austenitic temperatures (≈900–960 °C) in a carbon-rich atmosphere (gas, vacuum with hydrocarbon injection, or plasma). After sufficient diffusion time (2–10 h), the component is quenched and tempered to achieve a hard martensitic case and a tough tempered core.

The resulting microstructure typically exhibits:

High-carbon martensitic case

Transition gradient from high-carbon case to lower-carbon core

Retained austenite and carbides depending on process control and alloy composition

3.2 Typical Process Parameters

Table 2. Representative carburizing parameters for automotive gears and shafts.[5]

Parameter	Typical range (carburized gears/shafts)
Steel grades	16MnCr5, 20MnCr5, 18CrNiMo7-6, SAE 8620, SCM420
Temperature (°C)	900–960
Carbon potential (wt.% C)	0.8–1.1
Time at temperature (h)	2–12 (depending on desired case depth)
Case depth (mm)	0.8–1.5 (effective, at ~550 HV)
Quench medium	Oil, polymer, high-pressure gas (vacuum systems)
Tempering temperature (°C)	150–200
Surface hardness	58–64 HRC

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3.3 Performance Characteristics

3.3.1 Hardness and Wear Resistance

Carburized steels exhibit high surface hardness and improved wear resistance. Multiple studies report surface hardness in the 58–64 HRC range with substantial improvement in sliding and rolling wear resistance compared to quenched-and-tempered steels.

3.3.2 Fatigue Strength

Carburizing can increase rolling contact fatigue life by up to an order of magnitude, e.g. from ~10^7 to ≥10^8 cycles for bearing steels, and significantly enhance bending fatigue of gears through deep hardened layers and favorable residual stress profiles.

3.3.3 Distortion and Dimensional Control

High treatment temperature and quenching lead to:
Size change (growth/shrinkage) due to phase transformation and carbon gradients
Distortion (bending, warping, ovality) especially in slender components
These issues are often mitigated by:
Low-pressure (vacuum) carburizing with high-pressure gas quenching
Careful fixturing and process control
Post-hard machining and grinding (adds cost and scrap risk)

3.4 Example Data and Conceptual Plots

Table 3. Typical effect of carburizing on mean fatigue limit of automotive gear steels (normalized to quenched-and-tempered, Q&T).

Property	Q&T baseline	Carburized	Relative change
Surface hardness (HRC)	32–40	58–62	+60–80%
Bending fatigue limit (MPa)	350–450	600–800	+40–80%
Rolling contact life (cycles)	1×10^7	≥1×10^8	≥10×
Wear rate (normalized)	1.0	0.3–0.5	−50–70%

Figure 2 (conceptual): S–N curves for Q&T vs carburized specimens showing right-shifted curves and increased fatigue limit for carburized gears. Adapted qualitatively from rolling contact and high-cycle fatigue studies.

4. Plasma Nitriding of Automotive Components

4.1 Process Description and Microstructure

Plasma (ion) nitriding is a glow-discharge process conducted typically at 450–580 °C in N_2–H_2 (sometimes Ar) atmospheres. Nitrogen ions are accelerated toward cathodically biased components, generating active nitrogen species that diffuse into the steel.
Resulting microstructures often consist of:
A thin compound layer (white layer) of γ′-Fe_4N and ε-$Fe_{2–3}N$ (5–25 μm)
A diffusion zone (50–400 μm) enriched with fine nitrides and high compressive residual stresses
Plasma nitriding is especially attractive for complex geometries and precise control of case depth via process parameters such as gas composition, pressure, bias voltage and time.

4.2 Typical Process Parameters

Table 4. Representative plasma nitriding parameters for automotive components.

Parameter	Typical range
Steel grades	Nitriding steels, low alloy steels, tool steels
Temperature (°C)	450–580
Gas composition (vol.%)	20–60% N_2, balance H_2 (+Ar optional)
Pressure (Pa)	200–1000
Time (h)	4–20
Compound layer thickness (μm)	5–25
Diffusion zone depth (mm)	0.2–0.7
Surface hardness (HV)	900–1200
Distortion	Very low (no martensitic quench)

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4.3 Performance Characteristics

4.3.1 Hardness, Wear and Friction

Plasma nitriding significantly increases surface hardness of steels (up to 900–1200 HV), resulting in strong reductions in wear rate. Studies on automotive gears and other components show lower wear intensity than carburized counterparts under similar loads, sometimes by ~50% at moderate contact pressures.

4.3.2 Fatigue Behavior

Nitriding increases near-surface compressive residual stresses and eliminates micro-crack initiation sites, leading to large increases in fatigue limit:
Fatigue limit increases of 50–115% compared to Q&T steels reported for smooth and notched specimens.
Bending fatigue resistance of nitrided gears often exceeds that of carburized gears with similar core strength due to stronger net compressive stress and absence of quenching distortion.

4.3.3 Distortion and Dimensional Accuracy

Because plasma nitriding is performed in the ferritic region (no austenitization) and does not require quenching, dimensional changes and distortion are minimal. Components can often be nitrided after final machining, reducing overall processing time and cost.

4.4 Example Data and Conceptual Plots

Table 5. Typical performance changes due to plasma nitriding (normalized to Q&T).

Property	Q&T baseline	Plasma nitrided	Relative change
Surface hardness (HV)	300–400	900–1200	+200–250%
Bending fatigue limit (MPa)	350–450	550–800	+50–115%
Wear rate (normalized)	1.0	0.2–0.5	−50–80%
Distortion (qualitative index)	High	Very low	–

Figure 3 (conceptual): Bar chart of normalized fatigue limit for Q&T, carburized and plasma nitrided steels showing highest normalized fatigue for plasma nitrided specimens (≈1.4–1.8 vs 1.3–1.6 for carburized).

5. Nitrocarburizing of Automotive Components

5.1 Process Description and Microstructure

Nitrocarburizing introduces nitrogen and carbon simultaneously into steel at ferritic or austenitic temperatures. Ferritic nitrocarburizing (FNC) is most common for automotive applications and is typically performed at ~500–580 °C in gas or salt baths, or by plasma processes.
The characteristic microstructure comprises:
Compound layer: ε-$Fe_{2–3}$(N,C) carbonitride “white layer” (~5–25 µm) with excellent anti-scuffing and wear resistance
Diffusion zone: nitrogen-enriched ferrite with dispersed nitrides and carbonitrides, providing enhanced fatigue strength
Variants such as QPQ (quench-polish-quench) add post-oxidation to form a thin oxide layer, further improving corrosion resistance (e.g., brake discs, shock absorber rods).

5.2 Typical Process Parameters

Table 6. Representative nitrocarburizing parameters for automotive components.

Parameter	Typical range
Steel grades	Low-carbon steels, gray cast iron, low-alloy steels
Temperature (°C)	500–580 (ferritic); up to ~700 (austenitic)
Atmosphere / salt	NH_3 + C-donor gas; cyanate/cyanide salts; plasma
Time (h)	1–6 (often shorter than nitriding/carburizing)
Compound layer thickness (µm)	5–20
Diffusion zone depth (mm)	0.1–0.5
Surface hardness (HV)	700–1100
Post-oxidation	Optional (QPQ)
Distortion	Very low

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5.3 Performance Characteristics

5.3.1 Wear and Corrosion

Nitrocarburizing excels in combined wear and corrosion performance:
FNC-treated brake discs exhibit significant reductions in pad and disc wear and stable friction coefficients compared to untreated gray cast iron discs.
Post-oxidized nitrocarburized surfaces show marked improvements in corrosion resistance relative to carburized or plain nitrided surfaces.

5.3.2 Fatigue Performance

Nitrocarburizing improves fatigue life via compressive residual stress and surface hardening. Studies on valves and spring elements report increased service life and reduced crack initiation rates, with life extension often in the 2–4× range relative to untreated components.

5.3.3 Dimensional Stability

Because nitrocarburizing is conducted in the ferritic region, distortion is minimal and is typically less than that of gas nitriding and substantially less than carburizing. Dimensional changes are often within a few micrometers, allowing treatment after finish machining for many components.

5.4 Example Data and Conceptual Plots

Table 7. Typical performance changes due to nitrocarburizing (normalized to untreated material).

Property	Untreated	Nitrocarburized	Relative change
Surface hardness (HV)	200–250	700–1100	+200–350%
Wear rate (normalized)	1.0	0.2–0.4	−60–80%
Corrosion rate (normalized)	1.0	0.2–0.5	−50–80%
Service life (valves/springs)	1.0	2–4	+100–300%

Figure 4 (conceptual): Plot of wear rate vs contact pressure for carburized vs ion-nitrided vs nitrocarburized samples; nitrocarburized and nitrided show lower wear at moderate pressures, with nitrocarburized samples offering best combined wear–corrosion performance.

6. Comparison of Process Parameters

To make engineering decisions, process parameters must be compared not only on performance but also on temperature window, cycle time and process complexity.

6.1 Process Parameter Matrix

Table 8. Comparative process parameter matrix for case hardening technologies.

Parameter	**Carburizing**	**Plasma Nitriding**	**Nitrocarburizing (FNC)**
Temperature (°C)	900–960	450–580	500–580
Treatment time (h)	4–12	4–20	1–6
Case depth (mm)	0.8–1.5	0.2–0.7	0.1–0.5
Surface hardness	58–64 HRC	900–1200 HV	700–1100 HV
Quench required	Yes	No	No/mild
Distortion risk	High	Low	Very low
Atmosphere control	Carbon potential	Nitrogen potential, bias	N + C potential, sometimes oxide
Energy consumption (relative)	High	Moderate	Low–moderate
Typical cycle complexity	Medium–high	High (power, control)	Medium

Figure 5 (conceptual): Stacked bar chart of process temperature and cycle time illustrating the high-temperature/long-cycle nature of carburizing vs shorter, lower-temperature nitrocarburizing.

7. Comparative Analysis of Performance Characteristics

This section compares the effect of the three processes on key performance metrics for automotive components: hardness, wear, fatigue, corrosion, distortion and noise/vibration implications.

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7.1 Surface Hardness and Case Depth

Table 9. Comparison of hardness and case depth ranges for typical automotive steels.

Metric	Carburizing	Plasma Nitriding	Nitrocarburizing
Surface hardness	58–64 HRC	900–1200 HV	700–1100 HV
Effective case depth (mm)	0.8–1.5	0.2–0.7	0.1–0.5
Hardness gradient	Gradual to ductile core	Sharp gradient	Sharp gradient
Compound/white layer	No (martensitic case)	γ′, ε nitride layer	ε carbonitride layer

Carburizing achieves the deepest case, ideal for heavily loaded gears and shafts subjected to high bending and rolling contact stresses. Plasma nitriding and nitrocarburizing form thinner but very hard compound layers and diffusion zones, ideal where wear and corrosion dominate and deep bending stresses are lower or can be managed through geometry.

7.2 Wear and Friction

Table 10. Qualitative comparison of wear behavior under typical automotive contact conditions.

Application	Carburizing	Plasma Nitriding	Nitrocarburizing
Gear tooth flank (rolling/sliding)	Very good pitting & wear resistance	Excellent; lower wear at same case depth	Very good; best anti-scuffing at shallow depth
Brake disc (sliding)	Rarely used	Limited use	Widely used (FNC + post-oxidation)
Shock absorber rod	Not typical	Limited use	Common QPQ-type treatments
Valve train (cam/follower)	Widely used historically	Increasingly used	Used for specific parts

Wear tests generally show:
Nitrided samples often exhibit ≈50% lower wear intensity than carburized ones under identical conditions.
Nitrocarburized surfaces offer the best scuffing resistance, particularly under boundary lubrication and low-speed sliding (common in brake discs and hydraulic rods).

7.3 Fatigue (Bending and Rolling Contact)

Table 11. Normalized fatigue performance for gear/shaft steels (baseline = Q&T).

Process	Normalized bending fatigue limit	Normalized rolling contact life
Q&T (baseline)	1.0	1.0
Carburizing	1.4–1.8	5–10
Plasma nitriding	1.5–2.0	4–8
Nitrocarburizing	1.3–1.7	3–6

Carburizing yields exceptional rolling contact fatigue life due to deep hardened cases.

Plasma nitriding offers slightly better bending fatigue for a given component thickness due to higher compressive residual stress and the absence of quench-induced tensile stress, improving endurance limits by ~50–115%.
Nitrocarburizing provides good overall fatigue properties, especially in contact fatigue for springs, valves and brake components.
Figure 6 (conceptual): Combined plot of normalized bending fatigue vs normalized rolling contact life showing carburizing as “RCF champion,” plasma nitriding as “bending fatigue champion” and nitrocarburizing offering balanced performance.

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7.4 Corrosion Resistance

Carburized surfaces typically require additional coatings for corrosion protection. Nitrided surfaces offer modest improvements depending on steel composition, but nitrocarburized (especially post-oxidized) surfaces provide pronounced corrosion resistance, reducing corrosion rates by up to ~50–80% in various test media.

7.5 Distortion and NVH Implications

Distortion affects gear microgeometry and therefore noise and vibration:

Carburizing: Highest distortion; requires grinding and careful gear correction, increasing cost but allowing very high load-carrying capacity.

Plasma nitriding / Nitrocarburizing: Minimal distortion; components can be treated after final machining, preserving tooth geometry and reducing NVH tuning effort.

8. Comparative Analysis of Life Cycle of Automotive Components

Life cycle can be considered in terms of:

Technical life (cycles, km, hours to failure)

Life-cycle cost (processing cost, scrap and rework, energy)

Sustainability (energy use, emissions, reusability)

8.1 Relative Life Extension

Table 12. Indicative life extension of various automotive components (normalized to conventional Q&T or untreated state; ranges derived from multiple studies).

Component / failure mode	Process	Relative life factor
Gear (bending fatigue)	Carburized	3–5
Gear (bending fatigue)	Plasma nitrided	3–6
Gear (pitting / RCF)	Carburized	5–10
Gear (pitting / RCF)	Plasma nitrided	4–8
Brake disc (pad/disc wear)	Nitrocarburized	2–4
Valve (spring/seat fatigue)	Nitrocarburized	2–4
Shaft (fretting fatigue)	Plasma nitrided	2–3

Data indicate that all three processes can at least double component life relative to untreated or Q&T states, with carburizing and plasma nitriding especially beneficial for gearing, and nitrocarburizing particularly effective for sliding/tribo-corrosion contexts.

8.2 Life-Cycle Cost Considerations

Table 13. Qualitative life-cycle cost comparison.

Cost element	Carburizing	Plasma Nitriding	Nitrocarburizing
Capital equipment	Furnace + quench	Plasma furnace (higher)	Furnace/salt/plasma (medium)
Process energy	High (high T + quench)	Medium	Low–medium
Distortion rework (grinding)	High	Low	Very low
Scrap rate	Higher	Lower	Lower
Throughput (for same case depth)	Lower	Moderate	Higher (shallower case)

From a life-cycle perspective:

Carburizing maximizes gear durability but at higher process and rework cost.

Plasma nitriding can be more cost-effective for components where a thinner case is sufficient, particularly when reduced grinding and lower scrap outweigh higher furnace cost.

Nitrocarburizing often provides the lowest total cost for parts where moderate case depth is acceptable but wear and corrosion resistance are critical (e.g., brake discs, suspensions).

8.3 Sustainability and Environmental Aspects

Gas carburizing historically used endothermic atmospheres with hydrocarbons and sometimes toxic carriers; modern vacuum carburizing greatly reduces emissions but still has high energy demand. Plasma nitriding and nitrocarburizing,

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especially low-pressure variants, can be more energy efficient and often produce less hazardous waste than salt-bath processes, though salt-bath nitrocarburizing still sees use with appropriate waste management.

9. Data-Driven Conclusion

To satisfy the requirement that the conclusion be expressed in the form of data, this section presents a consolidated scoring matrix and key numerical indicators summarizing the comparative performance of carburizing, plasma nitriding and nitrocarburizing for automotive applications.

9.1 Normalized Performance Score Matrix

Scores from 1 (poor) to 5 (excellent), compiled from the comparative data in Sections 3–8.

Table 14. Overall normalized scores (1–5) for automotive applications.

Criterion / Process	Carburizing	Plasma Nitriding	Nitrocarburizing
Surface hardness	4.5	5.0	4.5
Case depth	5.0	3.5	3.0
Bending fatigue	4.5	5.0	4.0
Rolling contact fatigue	5.0	4.5	4.0
Wear resistance	4.5	5.0	5.0
Corrosion resistance	2.5	3.0	4.5
Distortion (reversed scoring)	2.0	4.5	5.0
Process energy (reversed)	2.5	3.5	4.0
Life-cycle cost (reversed)	3.0	3.5	4.0

Figure 7 (conceptual): Radar chart of the above scores showing:

Carburizing as optimal for deep case and RCF for heavily loaded gears.
Plasma nitriding as optimal for high bending fatigue with minimal distortion.
Nitrocarburizing as optimal for wear–corrosion–distortion balance in sliding components.

9.2 Key Numerical Conclusions

Based on the data synthesized:
Fatigue improvement:
Carburizing and plasma nitriding both increase gear bending fatigue limits from ~350–450 MPa to ~600–800 MPa (≈1.4–2.0×), with plasma nitriding often achieving the highest relative gains (up to +115%).
Rolling contact fatigue life increases by ≈5–10× for carburized gears and ≈4–8× for nitrided gears vs Q&T baselines.

Wear reduction:

For comparable steels and loads, plasma nitriding and nitrocarburizing typically reduce wear rates by ≈50–80% relative to Q&T states, and by ≈30–50% relative to carburized conditions in comparable test configurations.

Corrosion performance:

Post-oxidized nitrocarburized surfaces reduce corrosion rates by ≈50–80% vs untreated and carburized surfaces in standard corrosion tests, enabling 2–4× service life for brake discs and similar components.

Life extension factors (typical ranges):

Gears: life factor 3–10 depending on failure mode and process (carburizing and plasma nitriding).
Brake discs and valves: life factor 2–4 with nitrocarburizing (especially FNC + oxide).

Distortion and cost:

Distortion magnitude for carburized parts is typically an order of magnitude higher (tens of μm to >100 μm) than for nitrided/nitrocarburized counterparts (few μm), translating into substantial savings in grinding and scrap when plasma nitriding or nitrocarburizing is used for suitable components.

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9.3 Data-Based Process Selection Guideline

Table 15. Recommended process by dominant design criterion (scores 1–3).

Dominant design priority	Preferred process (1 = best)	2nd best	3rd best
Maximum gear load capacity (RCF + bending)	1: Carburizing	2: Plasma nitriding	3: Nitrocarburizing
High fatigue with minimal distortion (shafts, cams)	1: Plasma nitriding	2: Carburizing	3: Nitrocarburizing
Wear + corrosion for sliding components (brakes, rods)	1: Nitrocarburizing	2: Plasma nitriding	3: Carburizing
Lowest rework and scrap at moderate loads	1: Nitrocarburizing	2: Plasma nitriding	3: Carburizing
Deep case for shock-loaded parts	1: Carburizing	2: Plasma nitriding	3: Nitrocarburizing

In summary, carburizing remains the process of choice for heavily loaded gears and shafts requiring deep case depths and maximum rolling contact fatigue life; plasma nitriding is superior where high bending fatigue, minimal distortion and high surface hardness are critical; and nitrocarburizing is best suited to components where a shallower but very hard and corrosion-resistant surface layer with minimal distortion and high wear/scuffing resistance is desired, such as brake discs, rods and valve components.

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