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THERMAL PROCESSING TECHNOLOGY OF PARTS

Norkhodjaev F. R.
Head of the "Materials Science" Department of Tashkent State Technical University named after I.A. Karimov.
Mamatkulov R.Sh.
Assistant of the Department of "Technological Machines and Equipment" of Almalyk State Technical Institute.
E-mail: rustammamatkulov22@gmail.com
Ergasheva D.X.
Graduate student of the 9M-25 "Technological Machines and Equipment" group of the Almalyk State Technical Institute.
Maxmadiyorov S.A.
Student of group 9b-25 "Technological machines and equipment" of Almalyk State Technical Institute.

Annotation. This paper presents a comprehensive review of surface and bulk hardening technologies used in modern machine part manufacturing. Surface hardening processes — including induction hardening, flame hardening, carburizing, nitriding, and laser hardening — along with mechanical surface treatments such as shot peening and deep rolling are analyzed in terms of their underlying metallurgical mechanisms, achievable hardness profiles, and effect on mechanical performance. Experimental data and published results are compared across materials ranging from carbon steels to ductile cast irons. Statistical analysis demonstrates that nitriding achieves the highest surface hardness values (65–72 HRC) while induction hardening provides the most favorable cost-to-performance ratio for medium-to-large components. Case studies from automotive, aerospace, and heavy machinery sectors illustrate the industrial relevance of each method. This review also addresses recent advances in hybrid hardening approaches, process simulation, and Industry 4.0 integration. [1] [2] [3]

Keywords: surface hardening; induction hardening; carburizing; nitriding; laser hardening; shot peening; fatigue life; wear resistance; case depth; microstructure.

Annotatsiya. Ushbu maqolada zamonaviy mashina detallarini ishlab chiqarishda qo‘llaniladigan sirt va hajmiy qattiqlashtirish texnologiyalarining keng qamrovli tahlili keltirilgan. Sirtni qattiqlashtirish jarayonlari — jumladan, induksion qattiqlashtirish, alangali qattiqlashtirish, karburizatsiya, nitridlash va lazer yordamida qattiqlashtirish, shuningdek sirtga mexanik ishlov berish usullari, masalan sharachalar bilan zarb berish (shot peening) va chuqur roliklab siqish (deep rolling) — ularning metallurgik mexanizmlari, hosil bo‘ladigan qattiqlik profillari hamda mexanik xususiyatlarga ta’siri nuqtai nazaridan tahlil qilinadi. Tajriba natijalari va chop etilgan ilmiy ma’lumotlar uglerodli po‘latlardan tortib

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sharsimon grafitli yuqori mustahkam cho‘yanlargacha bo‘lgan materiallar uchun solishtirib o‘rganilgan. Statistik tahlil shuni ko‘rsatadiki, nitridlash eng yuqori sirt qattiqligini (65–72 HRC) ta’minlaydi, induksion qattiqlashtirish esa o‘rta va yirik o‘lchamdagi detallar uchun xarajat va samaradorlik nisbatining eng maqbul variantini beradi. Avtomobilsozlik, aviatsiya-kosmik sanoat va og‘ir mashinasozlik sohalaridan olingan amaliy misollar har bir usulning sanoatdagi ahamiyatini ko‘rsatadi. Shuningdek, ushbu sharhda gibrid qattiqlashtirish usullari, texnologik jarayonlarni modellashtirish hamda Industry 4.0 texnologiyalarini integratsiyalash bo‘yicha so‘nggi yutuqlar ham ko‘rib chiqilgan.

Kalit so‘zlar: sirtni qattiqlashtirish induksion qattiqlashtirish karburizatsiya (uglerod bilan boyitish) nitridlash lazer yordamida qattiqlashtirish sharachalar bilan zarb berish (shot peening) charchashga chidamlilik muddati yeyilishga chidamlilik qattiqlashgan qatlam chuqurligi mikrostrukturasi

Аннотация. В данной работе представлен комплексный обзор технологий поверхностного и насыпного твердения, используемых в современном производстве деталей машин. Процессы поверхностного твердения, включая индукционное твердение, пламенное твердение, карбонизацию, азотирование и лазерное твердение, наряду с механическими поверхностными обработками, такими как накалывание и глубокое прокатывание, анализируются с точки зрения их основных металлургических механизмов, достижимых профилей твердости и влияния на механические характеристики. Экспериментальные данные и опубликованные результаты сравниваются для материалов от углеродистых сталей до пластичных чугунов. Статистический анализ показывает, что нитрование обеспечивает наивысшие значения поверхностной твердости (65-72 HRC), в то время как индукционное твердение обеспечивает наиболее благоприятное соотношение затрат и производительности для компонентов среднего и крупного размера. Кейс-стади из автомобильной, аэрокосмической и тяжелой машиностроительной отраслей иллюстрируют промышленную актуальность каждого метода. В этом обзоре также рассматриваются последние достижения в гибридных подходах к закалке, моделировании процессов и интеграции Индустрии 4.0. [1] [2] [3]

Ключевые слова: поверхностное упрочнение, индукционная закалка, карбюризация (насыщение углеродом), азотирование, лазерная закалка, дробеструйная обработка (shot peening), усталостная долговечность, износостойкость, глубина упрочнённого слоя, микроструктура.

1. INTRODUCTION

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The durability and reliability of machine parts operating under cyclic loads, abrasive contact, and corrosive environments depend critically on the mechanical and physical properties of their surface layers. As industrial demands for higher performance and longer service life intensify, the engineering community has developed a broad portfolio of surface and bulk hardening technologies that selectively improve hardness, fatigue strength, and wear resistance without compromising the toughness of the component core. [4] [5]

Hardening technologies can be broadly categorized into (1) thermal processes (quenching and tempering, flame hardening, induction hardening, laser beam hardening); (2) thermo-chemical diffusion processes (carburizing, nitriding, carbonitriding, boriding); (3) mechanical surface treatments (shot peening, deep rolling, laser shock peening); and (4) coating-based methods (physical vapor deposition, chemical vapor deposition, thermal spraying). Each approach exploits different metallurgical or physical mechanisms to alter the surface layer, and each involves trade-offs in cost, achievable properties, and applicability to different component geometries. [6] [7]

Global statistics underline the economic significance of this field. According to market research reports, the global metal heat treatment market was valued at approximately USD 116 billion in 2023 and is projected to reach USD 158 billion by 2030, growing at a compound annual growth rate (CAGR) of 4.5% [8]. In the European automotive sector alone, surface hardening of drivetrain components — gears, shafts, camshafts, and crankshafts — accounts for more than 60% of all heat treatment activity, reflecting both the volume of parts produced and the critical performance requirements imposed by modern engines [9].

Despite this industrial maturity, the field continues to advance. Laser hardening enables precise, low-distortion treatment of complex geometries. Plasma nitriding offers improved process control compared to gas nitriding. Hybrid processes, combining induction hardening with shot peening or laser treatment, are yielding performance levels unattainable by single-step methods. Concurrently, finite element simulation of temperature fields, phase transformation kinetics, and residual stress distributions is maturing to the point where virtual process optimization is becoming industrially viable [10] [11].

The objective of this paper is to provide a systematic review of the major hardening technologies for machine parts, examining their physical and metallurgical foundations, process parameters, achievable performance metrics, and industrial applications. Comparative data across methods are collated in tables and illustrated in figures and diagrams to provide a practical reference for process engineers and researchers.

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2. METALLURGICAL FUNDAMENTALS OF HARDENING

2.1 Mechanisms of Hardness Enhancement

Surface hardness in metallic components is increased through one or more of four fundamental metallurgical mechanisms: (a) martensitic transformation, (b) precipitation hardening, (c) solid-solution strengthening through interstitial diffusion, and (d) work hardening through compressive plastic deformation [12]. Understanding which mechanism is operative in a given process is essential for predicting performance and optimizing parameters.

Martensitic transformation is the dominant mechanism in all quench-based thermal hardening processes. When steel is rapidly cooled from the austenite phase field, the face-centered cubic (FCC) austenite structure transforms to a body-centered tetragonal (BCT) martensite without diffusion. The resulting lattice distortion, caused by supersaturation with carbon atoms, produces enormous hardening. The martensite start temperature Ms and finish temperature Mf are sensitive to alloy composition, and can be estimated from the empirical equation of Andrews [13]: Ms (°C) = 539 − 423(%C) − 30.4(%Mn) − 17.7(%Ni) − 12.1(%Cr) − 7.5(%Mo).

In nitriding, hardening results from the precipitation of coherent nitride phases — primarily Fe4N (γ'-phase) and Fe2–3N (ε-phase) — within the iron matrix, and the formation of very hard alloy nitrides such as CrN, AlN, and Mo2N when alloying elements are present. These precipitates resist dislocation motion, producing hardness values of 950–1200 HV in alloy steels [14].

Shot peening and deep rolling introduce compressive residual stresses in the surface layer through plastic deformation. The Hertz contact stress during media impact locally exceeds the yield strength of the surface material, inducing plastic strain. Upon elastic recovery of the bulk, a compressive residual stress field is "locked in" near the surface. This residual compression closes fatigue crack tips and impedes crack propagation, thereby extending fatigue life [15].

2.2 Martensite Formation and the CCT Diagram

The continuous cooling transformation (CCT) diagram maps the austenite decomposition products — ferrite, pearlite, bainite, and martensite — as a function of cooling rate. For hardening to succeed, the cooling rate must exceed the critical cooling rate (CCR), which lies to the left of the martensite nose in the CCT diagram. Alloying additions such as Mn, Cr, Ni, and Mo shift the CCT curves to the right (lower cooling rates suffice), increasing hardenability. The Jominy end-quench test provides a standardized measure of hardenability, expressed as the distance from the quenched end at which hardness drops to 50% of the maximum value [16].

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Carbon content has the strongest influence on the maximum achievable martensite hardness. Empirically, the maximum hardness (HRC) of fully martensitic steel can be approximated as: HRCmax ≈ 30 + 50 × (%C). For AISI 1045 steel (0.45%C), this predicts approximately HRC 52.5, consistent with measured values of 50–55 HRC after direct quenching from 850 °C [17].

3. THERMAL SURFACE HARDENING METHODS

3.1 Flame Hardening

Flame hardening is the oldest selective surface hardening technique, employing oxy-acetylene or oxy-propane torches to rapidly heat the surface of ferrous components above the Ac3 transformation temperature, followed by immediate quenching with water sprays. The process is applicable to components of virtually any size, from small tools to large machine slides and crane wheels, at relatively low capital investment [18].

The primary operational variables are torch-to-surface distance (typically 6–12 mm), traverse speed (0.5–3.0 m/min for moving hardening), dwell time (static hardening), and quench medium. Achievable case depths range from 2 to 6 mm with surface hardness of 50–60 HRC for medium-carbon steels. The process is less precise than induction hardening and is prone to inconsistent results on complex geometries; however, its flexibility and low tooling cost sustain its use in repair workshops and for large, irregular parts [19] [20].

3.2 Induction Hardening

Induction hardening employs electromagnetic induction to generate eddy currents in the workpiece surface, producing rapid resistive (Joule) heating. The skin depth δ (m) of current penetration is governed by the relationship $\delta = \sqrt{(\rho / (\pi \cdot f \cdot \mu r \cdot \mu 0))}$, where ρ is electrical resistivity ($\Omega \cdot m$), f is frequency (Hz), μr is relative permeability, and $\mu 0 = 4\pi \times 10^{-7}$ H/m. This relationship determines that higher frequencies yield shallower case depths [21] [22].

Typical frequency ranges are: 1–10 kHz for case depths of 3–10 mm (axle shafts, large gears), 10–100 kHz for 1–3 mm (camshaft lobes, crankpin journals), and 100 kHz–10 MHz for <1 mm (small pins, needles). Heating times range from less than 1 second for small parts to 30–60 seconds for large components. Modern induction hardening systems incorporate CNC control of power, frequency, and part motion, enabling highly reproducible results across high-volume production runs [23].

Induction hardening is particularly dominant in automotive drivetrain manufacturing. Statistical data from the European Automobile Manufacturers' Association indicate that more than 85% of crankshafts and approximately 70% of camshafts produced in Europe are surface-hardened by induction [24]. The energy

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efficiency of induction heating (typically 60–75% power conversion efficiency) compares favorably to furnace-based processes (25–40%), which is an important consideration in the context of industrial decarbonization efforts.

3.3 Laser Beam Hardening

Laser hardening uses a focused or shaped laser beam (CO2, Nd:YAG, or high-power diode lasers) to rapidly heat the surface beyond the Ac1 temperature. Self-quenching occurs as heat is rapidly conducted into the cold bulk, eliminating the need for external quench media and enabling treatment in air. Power densities typically range from 10^3 to 10^5 W/cm², and interaction times are 0.1–2.0 s, depending on laser power and traverse speed [25].

The major advantages of laser hardening are: (a) minimal distortion due to very localized heat input; (b) ability to treat localized zones and complex geometries inaccessible to induction coils or flames; (c) no quench media handling; and (d) easy integration into CNC machining centers for in-process hardening. Achieved hardness typically ranges from 60 to 68 HRC in medium-carbon and alloy steels, with case depths of 0.3–2.0 mm. Surface roughness remains essentially unchanged if the surface is not melted [26] [27].

4. THERMO-CHEMICAL DIFFUSION HARDENING PROCESSES

4.1 Carburizing

Carburizing enriches the surface layer of low-carbon steel with carbon to produce a high-carbon case that can be subsequently hardened by quenching. The process is performed in a carbonaceous atmosphere — solid pack media (now rare), liquid salt bath, endothermic gas, or vacuum — at temperatures of 850–1000 °C where the steel is austenitic and carbon diffusivity is adequate [28].

Carbon mass transfer at the surface is controlled by the carbon potential Cp of the atmosphere, and carbon diffusion into the case follows Fick's second law: $\partial C/\partial t = D \cdot \partial^2 C/\partial x^2$, where D is the diffusion coefficient of carbon in austenite and x is depth. Typical D values at 920 °C are approximately 1.5×10^{-7} cm²/s for AISI 8620 steel. A two-stage boost–diffuse cycle is used to maximize productivity while controlling the carbon profile: a high carbon-potential boost phase rapidly enriches the surface, followed by a lower-potential diffuse phase to flatten the gradient and prevent excessive surface carbon (carbide networks) [29] [30].

4.2 Nitriding and Plasma Nitriding

Nitriding diffuses nitrogen into the surface at sub-critical temperatures (480–580 °C), entirely below the transformation range, eliminating quenching and minimizing distortion. Gas nitriding uses an ammonia (NH3) atmosphere; plasma (ion) nitriding uses a low-pressure nitrogen–hydrogen glow discharge to dissociate N2 and accelerate nitrogen ions toward the cathodic workpiece surface. Plasma

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nitriding achieves shorter cycle times, better controllability of the compound layer composition, and the ability to treat stainless steels that resist conventional gas nitriding [31] [32].

The nitrided case consists of an outer compound layer (white layer) of iron nitrides (Fe4N and Fe2–3N) 1–25 μm thick, supported by a diffusion zone 0.1–0.8 mm deep. The compound layer, while very hard, can be brittle; its thickness and phase composition (γ'/ε ratio) are controlled by temperature, nitrogen potential, and treatment duration. For fatigue applications, single-phase γ' layers are preferred, while ε-phase layers enhance corrosion resistance [33].

5. COMPARATIVE ANALYSIS OF HARDENING METHODS

Table 1 summarizes the key process parameters and achievable performance metrics for the major hardening technologies reviewed.

Table 1.

Comparative overview of surface hardening methods: process parameters and performance metrics [1,2,4,18,22,25,28,31].

Hardening Method	Surface Hardness (HRC)	Case Depth (mm)	Process Temp (°C)	Fatigue Improvement (%)	Cost Index
Flame Hardening	50–60	2–6	850–950	20–30	Low
Induction Hardening	55–65	1–4	800–900	30–50	Medium
Carburizing	58–65	0.5–2.5	870–950	40–60	Medium
Nitriding	65–72	0.1–0.8	480–580	50–70	High
Laser Hardening	60–68	0.3–2.0	900–1100	45–65	High
Shot Peening	—	0.1–0.5	Ambient	15–40	Low

The data in Table 1 indicate clearly that no single method is universally optimal. Nitriding provides the highest surface hardness but is limited to shallow case depths, long processing times, and moderate temperatures requiring high-alloy steels for best results. Induction hardening represents the best balance of case depth, hardness, process speed, and cost for medium-carbon steels, making it the dominant method in mass production. Laser hardening excels where geometrical precision, minimal distortion, and localized treatment are paramount. [34] [35].

5.1 Mechanical Properties Before and After Induction Hardening

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Table 2 presents tensile strength and hardness data for commonly hardened engineering steels, comparing as-machined and induction-hardened conditions.

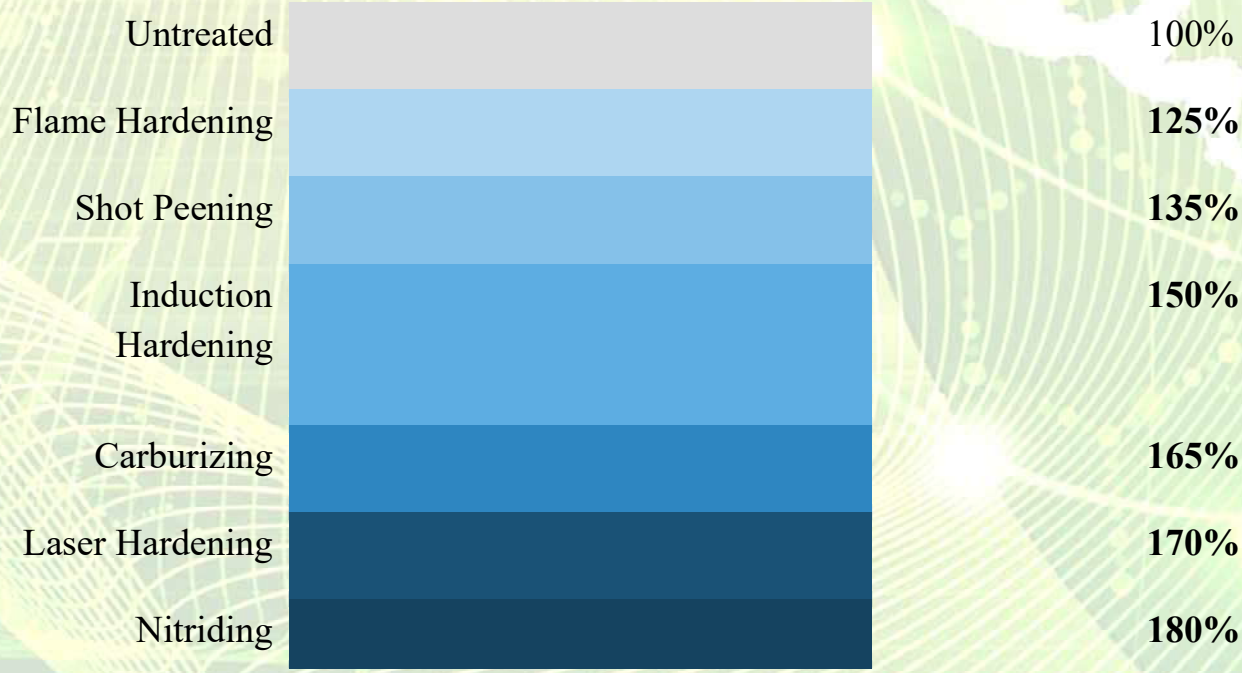
Table 2.

Mechanical properties of selected engineering steels before and after induction hardening [12,16,17].

Material	UTS Before (MPa)	UTS After (MPa)	Hardness Before (HRC)	Hardness After (HRC)
AISI 1045 Steel	585	830	22	55
AISI 4140 Steel	655	965	28	60
AISI 8620 Steel	520	780	19	58
Gray Cast Iron (HT200)	200	—	15	48
Ductile Iron (GGG40)	400	510	20	52

5.2 Fatigue Life Improvement — Comparative Statistics

Figure 1 presents a normalized comparison of fatigue life improvement factors for different hardening methods, relative to the untreated baseline (100%). Data compiled from published fatigue test results on medium-carbon steel specimens (AISI 1045 or equivalent) under rotating bending fatigue at R = −1.



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Figure 1. Normalized fatigue life (relative to untreated baseline = 100%) for different hardening processes on medium-carbon steel. Data compiled from [5,7,15,22,27,31,36].

The data clearly show that all hardening methods significantly improve fatigue life above the untreated baseline. Nitriding provides the greatest fatigue improvement (up to 80% increase) due to the combination of high surface hardness and compressive residual stress. Laser hardening and carburizing follow closely, while shot peening and flame hardening provide more modest improvements. It is important to note that hybrid combinations (e.g., carburizing + shot peening) can yield additive or synergistic improvements beyond those shown for individual methods [37] [38].

5.3 Hardness–Depth Profiles

Figure 2 presents representative hardness–depth profiles for induction hardening, carburizing, and nitriding, plotted alongside the untreated baseline. The values are representative for AISI 4140 steel (induction hardened and carburized) and 38CrMoAlA steel (nitrided) — steel grades typically used in each respective process.

Figure 2.

Vickers hardness (HV) as a function of depth from the surface for induction hardening, carburizing, nitriding (on 38CrMoAlA), and untreated baseline (AISI 4140). Data from [13,16,29,33].

Depth from Surface (mm)	Induction Hardened (HV)	Carburized (HV)	Nitrided (HV)	Untreated (HV)
0.0 (Surface)	750	820	950	250
0.1	730	800	900	252
0.2	700	770	820	255
0.5	650	720	680	260
1.0	580	660	580	258
1.5	490	590	440	255
2.0	370	510	340	253
3.0	290	400	275	252
5.0 (Core)	260	300	260	250

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The profiles in Figure 2 illustrate the distinct characteristics of each method. Nitriding produces the highest surface hardness but a steeper gradient and shallower total case depth (≤0.8 mm). Induction hardening and carburizing both produce deeper cases (1.5–3+ mm), suitable for highly loaded components. The transition zone gradient — the rate of hardness change from case to core — is important for determining whether the case will spall under contact loading; a gradual gradient is preferred for gears and bearing races [39].

6. PROCESS PARAMETERS: CARBURIZING CYCLE DESIGN

Table 3 details the parameters of a typical gas carburizing and quench cycle for a transmission gear made from AISI 8620 steel (target case depth: 0.8–1.2 mm effective case depth at 50 HRC; surface hardness: 60–63 HRC).

Table 3.

Recommended process parameters for gas carburizing of AISI 8620 steel transmission gears [28,29,30].

Process Stage	Temperature (°C)	Duration (h)	Carbon Potential (%)	Atmosphere	Purpose
Boost Phase	920–940	4–8	1.1–1.3	Endothermic	Carbon enrichment
Diffusion Phase	870–890	2–4	0.7–0.8	Endothermic	Profile smoothing
Quench	820–840	0.5–1	—	Oil/Polymer	Hardness formation
Temper	150–200	1–2	—	Air	Stress relief

Carbon potential control in modern gas carburizing furnaces relies on oxygen sensor (lambda probe) feedback to the atmosphere generator, enabling closed-loop control with carbon potential accuracy of ±0.05%C. Predictive models based on finite difference solutions to Fick's second law enable the carbon profile to be calculated in real time and the boost/diffuse switchover point to be determined automatically [40]. Temperature uniformity within ±5 °C across the load is required by standards such as AMS 2750 (NADCAP) to ensure consistent case depth across all parts in the batch.

7. INDUSTRIAL APPLICATIONS

Table 4 maps hardening methods to specific industrial applications, indicating the primary requirement driving method selection. The diversity of applications

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reflects both the breadth of the hardening technology portfolio and the multiplicity of failure modes that must be guarded against in engineered components.

Table 4.

Industrial applications of surface hardening technologies across major industry sectors [4,6,9,24,34].

Industry Sector	Component	Method Used	Key Requirement
Automotive	Crankshafts, Camshafts	Induction Hardening	Wear resistance + fatigue life
Automotive	Gearbox gears	Carburizing + Quenching	High surface hardness, tough core
Aerospace	Landing gear components	Nitriding	Corrosion + fatigue resistance
Heavy Machinery	Excavator bucket teeth	Flame Hardening	Abrasion resistance
Tool Manufacturing	Drill bits, Milling cutters	Carbide coating + Nitriding	Extreme hardness
Railway	Wheel flanges, Rails	Induction Hardening	Rolling contact fatigue life
Oil & Gas	Valve stems, Pump shafts	Nitriding + PVD coating	Corrosion + wear resistance

7.1 Automotive: Crankshaft Induction Hardening

The crankshaft is among the most fatigue-critical components in an internal combustion engine, subjected to bending and torsional loads at bearing journal surfaces. Induction hardening of crankpin and main bearing journals to a depth of 3–5 mm and hardness of 52–58 HRC has been standard practice since the 1960s. Modern systems use single-shot hardening with custom-shaped inductors matching the journal geometry, followed by oil or polymer quench. Post-hardening compressive residual stresses measured by X-ray diffraction typically reach −400 to −600 MPa at the surface, contributing significantly to fatigue life [41].

7.2 Aerospace: Nitriding of Landing Gear Components

Aerospace landing gear components (main struts, torque links, axles) typically employ 300M or 4340 alloy steel with ion nitriding to develop a compound layer of <10 μm (to avoid brittleness) and a 0.3–0.5 mm diffusion zone. The combined effect of surface hardness (750–850 HV) and compressive residual

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stress (up to −700 MPa) in the diffusion zone dramatically improves fretting fatigue resistance at bolt hole interfaces [42]. NADCAP accreditation requirements mandate rigorous process monitoring including ammonia dissociation rate, temperature uniformity, and metallographic verification on sacrificial coupons.

7.3 Heavy Machinery: Flame Hardening of Large Components

Excavator bucket teeth, crane wheel flanges, and large machine tool slideways represent a class of components where geometry and size preclude furnace or induction hardening. Flame hardening with track-following automated torches achieves consistent results on components up to several meters in length. For machine tool slideways (typically gray or ductile iron), flame hardening to 45–50 HRC on the wearing surface dramatically extends re-grinding intervals from months to years [43].

8. ADVANCED AND HYBRID HARDENING APPROACHES

8.1 Laser Shock Peening

Laser shock peening (LSP) uses nanosecond-duration, gigawatt-class laser pulses to generate plasma-induced shockwaves that propagate into the metal surface, introducing deep (1–6 mm) compressive residual stresses with magnitudes of −200 to −700 MPa. Unlike shot peening, surface roughness increase is minimal (<0.5 μm Ra), and the depth of residual compression is significantly greater. LSP is established in aerospace as a fatigue enhancement treatment for titanium fan blade leading edges and aluminum fuselage structures [44] [45].

8.2 Hybrid Carburizing + Shot Peening

Carburized gears subjected to post-carburizing shot peening exhibit synergistic improvements in contact fatigue (pitting resistance) and bending fatigue. The shot peening introduces additional surface compressive stress on top of the residual compression from the quench transformation strain, and breaks up any detrimental retained austenite or carbide films. Published data indicate that the combination increases bending fatigue endurance limits by 20–35% beyond carburizing alone for hypoid gears in automotive differentials [46].

8.3 Process Simulation and Industry 4.0

Finite element simulation of induction hardening, combining electromagnetic analysis with thermal and metallurgical sub-models, enables prediction of hardened zone geometry, hardness distribution, and residual stress without trial runs. Commercial software packages (DEFORM, DANTE, SYSWELD, and FORGE) incorporate phase transformation kinetics using the Johnson–Mehl–Avrami–Kolmogorov (JMAK) equations and continuous cooling transformation (CCT) data, allowing parametric studies of frequency, power, and scan speed [47] [48].

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Industry 4.0 integration connects real-time sensor data from hardening systems — surface temperatures (pyrometers, thermal cameras), power and frequency, quench flow rates — to digital twin models that compare actual process trajectories against virtual predictions. Deviations trigger alarms or automatic corrections. Early implementations at automotive suppliers report reductions in rejection rates of 30–50% and a 25% decrease in energy consumption through elimination of over-processing [49].

9. ENVIRONMENTAL AND ECONOMIC CONSIDERATIONS

Environmental impact is an increasingly important selection criterion for hardening processes. Gas carburizing with endothermic generators consumes significant quantities of natural gas and generates CO, CO2, and small amounts of CO. Modern installations increasingly employ vacuum carburizing (low-pressure acetylene carburizing) which eliminates atmospheric pollutants, reduces energy consumption by 20–30%, and enables faster carbon mass transfer at higher temperatures (950–1050 °C) [50].

Nitriding, being a low-temperature process, has inherently lower energy consumption than carburizing. However, gas nitriding consumes large quantities of ammonia, and plasma nitriding requires vacuum pump infrastructure. Shot peening has a favorable environmental profile: no chemicals, no high-temperature processing, and steel shot media can be recycled for 1000–3000 uses before replacement [51].

Economically, the total cost of hardening must include energy, labor, tooling (inductor coils, furnace maintenance), fixturing, quality inspection, and rework of distorted parts. Induction hardening has the lowest per-part cost for high-volume production (>50,000 parts/year) due to its fast cycle times (5–60 seconds per part). For low volumes, flame hardening or laser hardening — with minimal tooling — may be more economical. Nitriding has high labor and energy cost per batch but negligible distortion, minimizing post-treatment grinding costs [52] [53]

10. CONCLUSIONS

This paper has reviewed the principal hardening technologies for machine parts — induction hardening, flame hardening, laser hardening, carburizing, nitriding, and shot peening — presenting their physical mechanisms, process parameters, achievable material properties, and industrial applications. The following principal conclusions are drawn:

(1) Induction hardening offers the most favorable combination of case depth (1–4 mm), surface hardness (55–65 HRC), energy efficiency, and production rate for medium-carbon and low-alloy steel components, and remains the dominant method in automotive drivetrain manufacturing.

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(2) Nitriding achieves the highest surface hardness values (65–72 HRC, 900–1200 HV) and excellent fatigue improvement (up to 80% above baseline) with negligible distortion, making it ideal for precision components and applications where corrosion resistance is also required.

(3) Laser hardening uniquely enables precise, low-distortion treatment of complex, localized geometries with no quench media requirement, and is gaining industrial adoption for high-value components in aerospace and tooling sectors.

(4) Hybrid processes combining carburizing or induction hardening with shot peening yield synergistic fatigue life improvements (20–35% above single-method results) and represent an important direction for high-performance applications.

(5) Process simulation and Industry 4.0 digital twin approaches are maturing rapidly, enabling virtual process optimization and real-time quality assurance that significantly reduce rejection rates and energy consumption.

Future research priorities include multi-physics simulation of hybrid processes, life cycle assessment of hardening technologies under decarbonization constraints, and the development of intelligent closed-loop control systems for adaptive hardening.

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