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ELECTRON BEAM HARDENING AND SURFACE MODIFICATION – POSSIBILITIES AND APPLICATIONS OF THE TECHNOLOGY

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Abstract:
Electron beam (EB) hardening and surface modification are advanced surface-engineering technologies enabling precise, localized enhancement of material properties with minimal thermal effects on the bulk material. This review discusses the fundamental principles, process parameters, material responses, and industrial applications of electron beam surface treatment. Rapid heating and self-quenching during EB processing promote microstructural refinement and the formation of martensitic, bainitic, metastable, and nanostructured phases, leading to significant improvements in surface hardness, wear resistance, fatigue performance, and, in selected materials, corrosion resistance. The effects of key processing parameters, including beam energy, current, energy density, scanning speed, interaction time, and beam deflection, are considered. Applications in the automotive, aerospace, tooling, and medical sectors are presented, together with the main advantages and limitations of the technology. Electron beam processing is also compared with laser, induction, conventional heat treatment, ion beam, and plasma-based surface modification methods. Recent developments include hybrid treatments combining electron beam processing with nitriding and PVD coatings, pulsed electron beam technologies, compact accelerator systems, and advanced process monitoring. Future developments are expected to focus on Industry 4.0 integration, new material systems, hybrid processes, micro- and nanoscale surface engineering, sustainability, and broader industrial adoption.

Key words: electron beam hardening; surface modification; surface engineering; microstructural refinement; advanced manufacturing

INTRODUCTION

Electron beam (EB) technology has emerged as a highly effective and versatile method for surface hardening and modification in the production engineering field, offering unique advantages over conventional heat treatment processes.

The technology utilizes high-energy electron beams (typically 10-400 keV) with power densities ranging from 10^5 to 10^6 W/cm² to achieve heating rates up to 10^9 K/s, enabling precise surface modification without affecting bulk material properties. By employing accelerated electrons as a highly concentrated and precisely controllable energy source, electron beam processes enable precise localized heating, melting, and microstructural modification of materials often exceeding those achievable by conventional thermal or laser-based techniques. Studies on steels, cast irons, light alloys, and intermetallic compounds have demonstrated that electron beam hardening can produce hardened layers with depths

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ranging from several tens of micrometers to a few millimeters, depending on process parameters and material characteristics [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11].
The high power density of the electron beam, combined with rapid beam deflection and precise focusing, enables treatment of complex geometries and localized areas with high reproducibility, which is critical for modern engineering applications.
Industrial applications span automotive, aerospace, tooling, and medical device sectors, with particular success in treating gears, camshafts, turbine blades, cutting tools, and implants. The technology offers distinct advantages including minimal thermal distortion, high productivity, precise control, environmental friendliness, and the ability to combine with other surface treatments. Recent advances focus on hybrid technologies combining EB hardening with nitriding, PVD coatings, and additive manufacturing. Future trends point toward increased automation, integration with Industry 4.0 systems, development of compact accelerators, and expansion into new material systems and applications [2, 3, 4, 5, 6, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19].
This review aims to provide a comprehensive overview of electron beam hardening and surface modification, focusing on the underlying physical principles, process variants, and material responses. This is a narrative review. The cited literature spans 1987-2025 and includes experimental papers, reviews, conference papers and handbooks. The literature search was conducted mainly using ResearchGate and ScienceDirect databases. Studies are discussed by process regime, material response and manufacturing application. Particular attention is given to the possibilities offered by the technology, its current and emerging industrial applications in Europe and worldwide, as well as existing challenges and future research directions.

ELECTRON BEAM TECHNOLOGY IN MANUFACTURING

Electron beam technology has evolved from its origins in welding applications to become a sophisticated surface treatment method widely adopted in modern manufacturing. The technology utilizes accelerated electrons as an energy source to modify material surfaces through controlled thermal processes. Over the past several decades, electron beam surface treatment has transitioned from laboratory research to industrial-scale implementation, with over 1000 electron beam accelerator processors operating worldwide across diverse technological fields [1, 2, 3, 6, 11, 14, 16, 17, 18, 19, 20].
The fundamental appeal of electron beam technology in the production engineering field lies in its ability to deliver concentrated energy precisely to targeted surface regions while maintaining the bulk material at relatively low temperatures. This characteristic enables surface hardening and modification without the thermal distortion and dimensional changes typically associated with conventional bulk heat treatment processes. The technology has found particular relevance in industries demanding high-performance components with enhanced surface properties, including automotive, aerospace, tooling, and medical device manufacturing [1, 2, 3, 4, 5, 6, 11, 21, 22, 23, 24, 25, 26, 27]
Electron beam surface treatment encompasses several distinct processes, including surface hardening from solid and liquid states, surface alloying, cladding, remelting, and amorphization. Each process variant offers unique capabilities for tailoring surface properties to specific application requirements. The versatility of electron beam technology, combined with its precision and efficiency, has positioned it as a key enabling technology for advanced manufacturing in the 21st century [1, 2, 3, 4, 5, 6, 10, 11, 16, 17].
The development of modern electron beam systems has been driven by advances in accelerator technology, beam control systems, and process monitoring capabilities. Contemporary systems offer beam energies ranging from 30 keV up to 10 MeV, with precise control over beam parameters including power density, scanning speed, and energy distribution. These capabilities enable manufacturers to optimize surface treatment processes for specific materials and component geometries, achieving property enhancements previously unattainable through conventional methods [1, 2, 3, 4, 5, 6, 18, 19, 28, 29, 30].

FUNDAMENTAL PRINCIPLES OF ELECTRON BEAM HARDENING AND SURFACE MODIFICATION

The fundamental mechanism of electron beam surface treatment involves the conversion of kinetic energy from accelerated electrons into thermal energy upon interaction with the material surface [1, 4, 5, 9, 16, 17, 18, 19] (Fig. *1*).

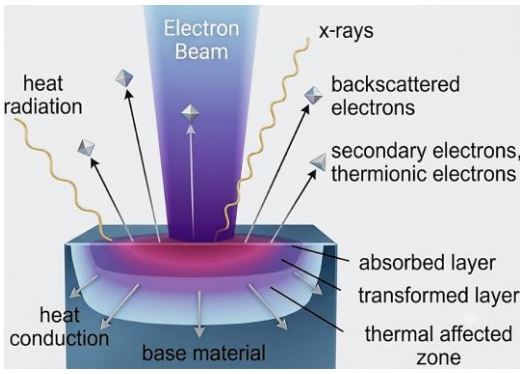


Fig. 1 Interaction of electron beam with matter

Alt text: *Schematic illustrating the interaction of an electron beam with a material surface, showing incident electrons penetrating the material and undergoing elastic and inelastic scattering, with backscattered electrons, secondary electrons, X-rays, and Auger electrons emitted from the interaction region.*

The hardening depth achievable for this technology depends primarily on the electron beam energy and the electron beam current, with typical hardening depths ranging from micrometers to millimeters [2, 5, 7, 11, 14].

Electron beam surface hardening operates through two primary thermal regimes: solid-state transformation hardening and melt-quench hardening. In solid-state hardening, the surface is rapidly heated above the austenization temperature and then quenched by heat conduction into the cold substrate, forming martensitic or bainitic structures. The extremely high heating and cooling rates produce fine-grained microstructures with enhanced mechanical properties [2, 5, 7, 11, 14, 15, 17].

In melt-quench processing, the electron beam melts a thin surface layer (typically 10-100 µm deep), which then undergoes rapid solidification at cooling rates of 10^4 to 10^8 K/s [28]. This rapid solidification produces refined grain structures, extended solid solubility, formation of metastable phases, and homogenization of composition [2, 5, 7, 11, 14].

PROCESS PARAMETERS AND THEIR EFFECTS

The effectiveness of electron beam surface treatment depends critically on several interrelated process parameters. The primary parameters include accelerating voltage (beam energy), beam current (power), energy density, scanning speed, pulse duration, and beam deflection pattern. For surface hardening applications, beam energies of 30-150 keV are commonly employed, delivering energy densities of 1,000-10,000 W/cm². The rapid heating rates achievable with electron beams, reaching up to 10^9 K/s for pulsed electron beams and up to 10^6 K/s for continuous electron beam sources, enable unique metallurgical transformations not possible with conventional heating methods. The energy density, defined as the energy delivered per unit area, represents the most critical parameter governing the depth and extent of surface modification. Energy density can be calculated from the electron beam power (which is which is the product of the accelerating voltage and the beam current) and sample movement speed. The sample movement speed plays the most crucial role. The sample's movement speed has the greatest influence on the heating rate and the cooling rate (Fig. *2*) of the near-surface layer, which determine the final phase composition and grain size [5, 7, 11, 18, 28, 29].

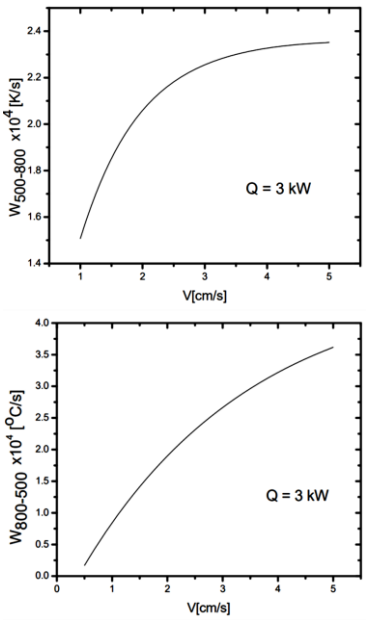


Fig. 2 Graphs representing: Calculated effect of sample's movement speed on heating rate (upper picture). Calculated effect of the sample's movement speed on the resulting cooling rate (lower picture)
Alt text: *Two graphs showing the calculated influence of sample movement speed on the thermal cycle during electron beam treatment. Upper: heating rate as a function of temperature for different movement speeds. Lower: corresponding cooling rate as a function of temperature, illustrating how movement speed affects heating and cooling behavior of the near-surface layer.*

Modern electron beam systems employ high-frequency beam deflection techniques to create uniform energy distribution over the treated area. Scanning speeds of several kilometers per second or scan frequencies around 100 kHz enable isothermal energy transfer to moving workpiece surfaces. The shape and frequency of beam deflection can significantly influence the profile of the hardened surface layer (Fig. 3, based on [28]).

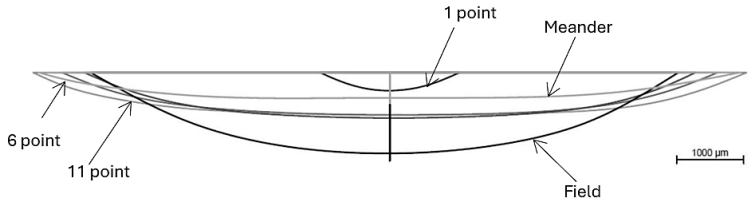


Fig. 3 Comparison of the profiles of hardened surface layers using different beam deflection shapes
Alt text: *Cross-sectional profiles of electron beam-hardened surface layers produced using different beam deflection patterns, illustrating variations in the shape, depth, and uniformity of the hardened zones.*

The three-dimensional energy transfer field created by beam deflection must be carefully matched to the material's surface geometry, heat conduction properties, and desired property gradients. High-frequency beam deflection enables productive electron beam surface treatment while maintaining precise control over the thermal cycle experienced by the material. The ability to dynamically adjust beam parameters during processing allows for treatment of complex geometries and creation of tailored property gradients [5, 6, 11, 17, 28, 31].
The interaction time between the electron beam and the workpiece surface fundamentally determines the thermal cycle and resulting microstructure [6]. The thermal cycle induced by electron beam treatment differs fundamentally from conventional heat treatment processes. The extremely high heating rates suppress grain growth during austenization, while the rapid cooling rates promote formation of fine martensitic or bainitic structures. The self-quenching effect, where heat conducts rapidly into the

cold substrate, eliminates the need for external quenching media and subsequent tempering operations [2, 5, 6, 11, 32, 33, 34].

Electron beam processing requires vacuum conditions to prevent scattering of the electron beam by gas molecules and to protect the heated surface from oxidation. Typical operating pressures range from 10^{-2} to 10^{-4} mbar, depending on the beam energy and required beam quality. While the vacuum requirement adds complexity and cost to the process, it provides the benefit of a clean, oxide-free surface after treatment [2, 4, 6, 10, 11, 16, 17, 18, 32, 35, 36, 37].

MATERIAL PROPERTIES ENHANCEMENT AND MICROSTRUCTURAL CHANGES

Hardness Enhancement

Electron beam surface treatment produces substantial increases in surface hardness across a wide range of materials. The results of our own analysis [15] showed that for 35HGS steel, an 83% increase in hardness was achieved when quenching at a speed of 500 mm/min, and a 71% increase when quenching at a speed of 100 mm/min. For 30HGSNA steel, the hardness increases for the corresponding sets of parameters were 28% and 21%, respectively. Another research [20] showed that for 35 HGS steel the average hardness of the layer hardened using an electron beam was slightly higher (680 HV) than the hardness of the LBH layer, whose average hardness value was 654 HV. The average hardness of the bainitised base material was 393 HV. Similar or even higher improvements have been reported for other steel grades, with some studies showing threefold increases in surface hardness [7, 23, 24, 28, 29, 30, 32, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48] – Table 1.

The hardness enhancement results from the formation of fine martensitic or bainitic structures, increased dislocation density, grain refinement, and formation of strengthening precipitates. The hardness profile typically shows a gradual transition from the hardened surface layer to the unaffected substrate, with the hardened depth controllable through adjustment of beam parameters [1, 7, 13, 31, 32, 40, 41].

Table 1

Selected base and treated hardness values with relation to steel composition

Ref.	Chemical composition						Base material hardness, HV	Hardened layer hardness, HV
	C, % wt	Cr, % wt	Mn, % wt	Si, % wt	Ni, % wt	Mo, % wt		
[28]	0,41	1,04	0,69	0,25	-	0,2	~300	< 740
[29]	0,42	0,96	0,6	0,37	-	-	~300	< 650
[30]	0,52-0,6	max. 0,25	0,50-0,80	0,17-0,37	< 0,25	-	~300	< ~ 627
[38]	2,2	12	0,4	0,4	-	-	650	< 1400
[39]	0,42	0,96	0,6	0,37	-	-	300	850
[23]	0,30-0,37	0,9-1,2	0,6-0,9	<0,4	-	0,15-0,3	~300	~650
[24]	0,28-0,34	0,8-1,1	0,8-1,1	0,9-1,2	< 0,3	-	~200	~500
[40]	0,41	1,1	1,02	0,25	0,015	-	~300	~650
[41]	0,5-0,6	0,6-0,9	1,2-1,6	0,25-0,6	1,4-1,8	0,15-0,30	355	< 656

Wear Resistance Improvement

Enhanced wear resistance represents one of the most significant benefits of electron beam surface treatment. Studies have demonstrated 4-10 fold improvements in wear resistance for various steel grades following electron beam treatment. The improved wear resistance correlates directly with the increased surface hardness and refined microstructure produced by the rapid thermal cycles [5, 7, 15, 22, 25].

For high-speed steel cutting tools, electron beam treatment of pre-quenched material significantly improved wear resistance through refinement of carbide distribution and formation of a hardened surface layer. The technology enables achievement of high abrasive wear resistance without hardening the

entire component cross-section, reducing residual stresses and associated distortion. This selective hardening capability proves particularly valuable for components requiring wear-resistant surfaces combined with tough, ductile cores [5, 6, 7, 12, 20].

Fatigue Life Enhancement

Electron beam surface treatment substantially improves fatigue performance through multiple mechanisms including surface hardening, residual stress modification, surface smoothing, and microcrack elimination. Formation of compressive residual stresses in the hardened surface layer inhibits crack initiation and propagation while smoothing effects can eliminate stress concentration sites [1, 5, 25, 26].

For commercially pure titanium, fatigue life increased 2.2-fold following pulsed electron beam treatment. Silumin alloys showed even more dramatic improvements, with fatigue life increasing 3.5 times. Steel components exhibited maximum fatigue life increases of 2.5-fold at optimal energy densities [1].

Microstructural Refinement

The rapid heating and cooling cycles characteristic of electron beam processing produce significant microstructural refinement. Grain sizes in the nanometer range can be achieved through pulsed electron beam treatment, with corresponding improvements in mechanical properties. The formation of nanosize grains, high dislocation densities, and dispersion of fine precipitates contributes to the enhanced properties [1, 5, 11, 13, 20, 28, 32, 38, 40, 41].

Electron beam hardening can transform the base microstructure of steels into various types of microstructure including bainite and martensite of different morphologies (Fig. *4* based on [28] and Fig. *5* based on [49])

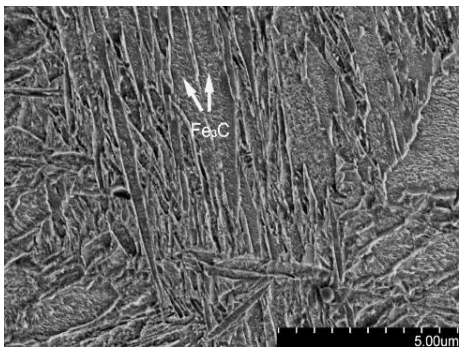


Fig. 4 Microstructure of 35 HGS steel hardened using an electron beam

Alt text: *Micrograph of electron beam-hardened 35 HGS steel showing a fine, needle-like transformed microstructure in the hardened region, resulting from rapid heating and subsequent self-quenching.*

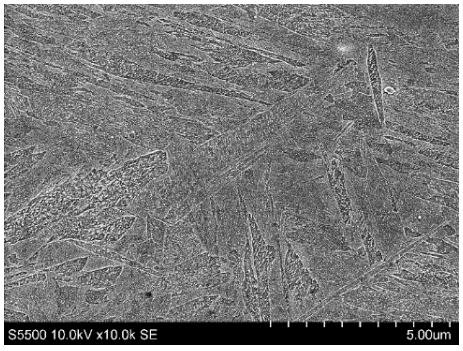


Fig. 5 Microstructure of 35 HGS steel hardened using an electron beam

Alt text: *Optical micrograph of 35 HGS steel after electron beam hardening, showing the transformed near-surface microstructure characterized by fine martensitic and bainitic features produced by rapid heating and self-quenching.*

These microstructural refinements directly correlate with the observed hardness increases. The near-surface layer quenched from the liquid state exhibits dissolution of second phases, formation of over-saturated solid solutions, and precipitation of nanosized segregates. These non-equilibrium structures provide property combinations unattainable through conventional processing [1, 5, 13, 28, 32, 38, 40, 41].

INDUSTRIAL APPLICATIONS IN THE PRODUCTION ENGINEERING FIELD

Automotive Industry

The automotive industry represents a major application area for electron beam surface hardening, particularly for powertrain components. Camshafts constitute a primary application, with electron beam hardening of controlling camshafts (Fig. *6* based on [50] and Fig. *7* based on [51]), calotte carriers, and related components achieving production rates of 3,500 parts per hour.



Fig. 6 Camshaft produced by KINTEK company. Visualisation of the EBH process
Alt text: *Photograph of a camshaft produced by KINTEK alongside a visualization of the electron beam hardening (EBH) process, showing a focused electron beam selectively treating the camshaft surfaces as the component rotates.*



Fig. 7 To the left: Cam sections hardened by Probeam company. To the right: Cross section of the same cam
Alt text: *Two images showing electron beam-hardened cam components. Left: cylindrical cam sections with selectively hardened cam surfaces. Right: cross-sectional view of a cam showing the electron beam-hardened surface layer along its outer profile.*

The technology enables selective hardening of cam lobes and bearing surfaces while maintaining core toughness, resulting in components with optimized property distributions [6, 20, 49]. Research on the application of electron hardening technology in the automotive industry [23], conducted by the Production Engineering Department at Isuzu Motors Ltd., demonstrated the high effectiveness of this method and enabled its application in industry. The material used for the tests was 34CrMo4 steel.
Cylinder liners, gears, and transmission components also benefit from electron beam surface treatment. The ability to harden specific regions without affecting the entire component reduces distortion and eliminates the need for post-hardening grinding operations in many cases. For gear applications, electron beam hardening of submicron bainitic steels has shown particular promise, offering an optimal surface hardening method for high-performance gears [5, 6, 20, 23, 31, 52] (Fig. *8* based on [20]).

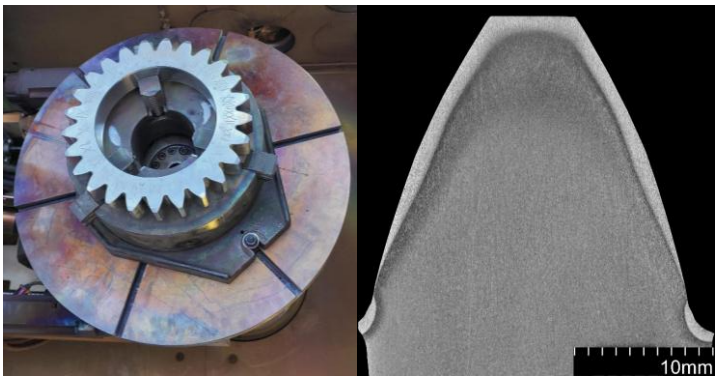


Fig. 8 To the left: Gear mounted to the CNC table of electron beam machine. To the right: Cross section of electron beam hardened tooth

Alt text: *Two images illustrating electron beam hardening of a gear. Left: gear mounted horizontally on the CNC positioning table of an electron beam processing machine. Right: cross-sectional view of a gear tooth showing the hardened surface layer along the tooth profile and the unaffected core material.*

Aerospace Applications

Aerospace components subjected to extreme operating conditions benefit significantly from electron beam surface modification. Turbine blades for aircraft engines receive electron beam treatment to improve fatigue resistance, wear resistance, and high-temperature oxidation resistance. The technology has proven effective for treating compressor blades, combustion chamber components, and rocket engine parts [1, 22, 24, 26, 27].

Titanium alloys, widely used in aerospace applications, respond particularly well to electron beam treatment. For Ti-6Al-4V alloy, electron beam processing improved fatigue characteristics, enhanced material strength, and produced nano-hardening of the surface and sub-surface layers. The treatment increased resistance to crack initiation and propagation while improving corrosion resistance. Aerospace applications also include treatment of precision parts for aircraft and rocketry, where the minimal distortion and precise control offered by electron beam processing prove essential [21, 24, 26, 27, 33].

Tooling and Die Manufacturing

Cutting tools, forming dies, and injection molding tools represent important application areas for electron beam surface hardening. For high-speed steel cutting tools, electron beam treatment of prequenched material improved wear resistance through microstructural refinement and optimized carbide distribution. The technology enables treatment of complex tool geometries, including selective hardening of cutting edges while maintaining tool body toughness [6, 12, 29, 31].

Cold forming tools and injection molding dies benefit from the combination of electron beam hardening with hard protective coatings. The electron beam treatment provides load-bearing support for the coating, significantly improving overall tool performance and life. Tool steels including C45, 31CrMoV9, 50CrV4, 100Cr6, X100CrMoV5-1, X155CrVMo12-1, and X220CrVMo13-4 have been successfully treated with electron beam technology for various tooling applications [6, 29, 31, 32, 38, 40, 45].

Medical Device Applications

Medical implants and surgical instruments benefit from electron beam surface modification, particularly for titanium alloys. Large area electron beam treatment of Ti-6Al-4V alloy, commonly used for hip and knee arthroplasties, improved fatigue characteristics, material strength, and surface corrosion resistance. The technology offers rapid, cost-effective surface modification suitable for processing complex implant surfaces [1, 26, 47].

Dental alloys have been successfully modified using pulsed electron beam treatment, with new methods developed specifically for this application. The ability to modify only the outer 10 µm layer without affecting bulk material properties proves particularly valuable for biomedical applications where both surface biocompatibility and bulk mechanical properties must be optimized. The technology also finds

application in manufacturing precision medical instruments requiring wear-resistant surfaces [1, 12, 26, 47].

Other Industrial Applications

Electron beam surface treatment extends to numerous other industrial sectors. In diesel engineering, the technology is applied for welding, hardening, and surfacing of critical components. Railroad rails receive electron beam treatment to improve wear resistance and fatigue life. Band saw blades and cutting bands benefit from electron beam welding and surface hardening [1, 5, 7, 10, 27].

Components for oil and gas storage, military equipment, and precision mechanical assemblies utilize electron beam processing. The technology has also found application in electronics and electrical industries for joining and surface modification of specialized components. The versatility of electron beam processing enables its application across diverse manufacturing sectors requiring enhanced surface properties [1, 5, 7, 10, 18, 27, 47].

ADVANTAGES AND LIMITATIONS

Advantages

Electron beam surface hardening offers numerous advantages over conventional heat treatment and competing surface modification technologies. The primary advantage lies in the precise, localized energy deposition that enables surface hardening without heating the bulk material to critical temperatures. This characteristic minimizes thermal distortion and eliminates the need for post-treatment straightening operations in many applications [1, 2, 3, 3, 4, 5, 6, 7, 10, 11, 12, 31].

The extremely high heating rates achievable with electron beams (up to 10^9 K/s) enable unique metallurgical transformations and microstructural refinement not possible with conventional heating methods. The self-quenching effect eliminates the need for external quenching media and subsequent tempering operations, simplifying the process and reducing costs. The technology offers high productivity, with modern systems achieving output rates of 3,500 parts per hour for automotive components [1, 2, 3, 4, 5, 7, 10, 11, 12].

Electron beam processing provides exceptional flexibility through precise control of beam parameters, enabling treatment of complex geometries and creation of tailored property gradients. The vacuum environment ensures clean, oxide-free surfaces and prevents contamination during processing. The technology is environmentally friendly, producing no chemical waste or emissions. The ability to combine electron beam hardening with other surface treatments such as nitriding and PVD coatings opens new possibilities for property optimization. [1, 2, 3, 4, 5, 6, 7, 10, 11, 12, 27, 28, 29, 30, 31].

Limitations

Despite its numerous advantages, electron beam surface treatment faces several limitations that constrain its application. The requirement for vacuum processing adds complexity, cost, and cycle time compared to atmospheric processes. The vacuum chamber size limits the dimensions of components that can be treated, although large-scale systems have been developed for specific applications [26, 27, 31].

The capital investment for electron beam equipment is substantial, requiring sophisticated accelerators, vacuum systems, beam control systems, and safety equipment including X-ray shielding. This high initial cost limits adoption primarily to high-value applications where the benefits justify the investment. The technology requires skilled operators and careful process control to achieve consistent results [2, 5, 6, 27].

The depth of hardening achievable with electron beam processing is limited compared to some competing technologies, typically ranging from 0.1 to 2.5 mm depending on material and parameters. For applications requiring deeper case depths, alternative methods may be more suitable. The treatment of highly reflective materials can be challenging due to reduced energy absorption. Precise seam

preparation and fixturing are required to ensure consistent beam interaction with the workpiece surface [2, 5, 6, 11, 14, 27, 31].

Economic Considerations

The economic viability of electron beam surface hardening depends on several factors including production volume, component value, and the specific property requirements. For high-volume automotive applications, the high productivity and elimination of post-processing operations provide favorable economics. The reduced distortion and improved dimensional stability can eliminate costly grinding operations, offsetting the higher processing cost [2, 5, 6, 46].

The technology proves most economical for high-value components where the enhanced properties justify the processing cost, such as aerospace components, precision tooling, and medical implants. The ability to extend component life through improved wear and fatigue resistance provides long-term economic benefits that may outweigh the initial processing cost. The environmental benefits and elimination of chemical waste disposal costs also contribute to the overall economic attractiveness [1, 6, 26, 29].

RECENT ADVANCES AND INNOVATIONS

Hybrid Technologies

Recent research has focused on combining electron beam hardening with complementary surface treatments to achieve synergistic property enhancements. The combination of electron beam hardening with nitriding has proven particularly successful, with the hybrid treatment increasing hardness by approximately 200 HV0.3 compared to electron beam hardening alone. The sequence of treatments critically affects the results, with both electron beam hardening followed by nitriding and the reverse sequence offering distinct advantages [6, 35, 39].

The combination of electron beam hardening with PVD hard coatings based on Ti(C)N, TiAlN, Cr_xN_y, and DLC has opened new application fields for highly loaded tools and components. The electron beam treatment provides load-bearing support for the coating, significantly improving bulk material load support, surface hardness, and critical loads. The hybrid technology reduces distortion compared to conventional bulk hardening followed by coating [6, 29, 33, 39, 46].

Pulsed Electron Beam Technology

High-current pulsed electron beam (HCPEB) technology (**Błąd! Nie można odnaleźć źródła odwołania.**) has emerged as a distinct variant offering unique capabilities for surface modification.

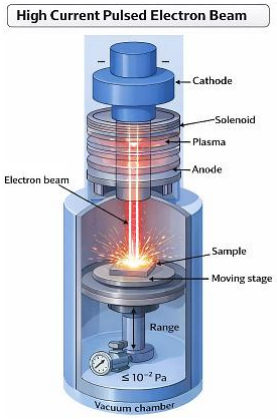


Fig. 9 Schematic of the construction of a device for pulsed electron beam processing based on pseudo-spark discharge power supply

Alt text: *Schematic of a high-current pulsed electron beam (HCPEB) device powered by a pseudo-spark discharge system. The setup consists of a cathode, solenoid, plasma region, and anode that generate and direct the electron beam toward a sample mounted on a movable stage inside a vacuum chamber.*

Pulsed systems employing low energy (10-40 keV), high current (up to 30 kA), and short pulse durations (2-40 μs) produce rapid melting and solidification cycles that create non-equilibrium structures. The technology has been intensively developed over the past few decades for phase transformation strengthening, surface remelting, surface alloying, and amorphous transformation [1, 12, 13, 37, 42, 43, 44, 45].

Pulsed electron beam processing produces several unique effects including surface smoothing, microcrack elimination, and formation of nanosize grains. The shock wave effects generated by pulsed treatment create zones of high stress that extend the modified layer beyond the heat-affected zone. Research continues on expanding the application scale of HCPEB technology to broader industrial implementation [1, 13, 30, 42, 43, 44, 45].

Process Monitoring and Control

Advances in process monitoring and control systems have improved the consistency and reliability of electron beam surface treatment. Modern systems incorporate real-time monitoring of beam parameters, workpiece temperature, and surface conditions. The integration of advanced sensors and control algorithms enables adaptive process control that compensates for variations in material properties and geometry [11].

The development of accurate process models and simulation tools has enhanced the ability to predict treatment results and optimize parameters for new applications. These tools enable virtual process development, reducing the time and cost required to implement electron beam hardening for new components. The incorporation of machine learning and artificial intelligence techniques promises further improvements in process optimization and quality control [6, 11].

Compact Accelerator Development

The development of compact, low-cost electron beam accelerators has been a focus of recent research aimed at expanding the accessibility of the technology. New generation compact in-line and stand-alone accelerators offer reduced capital costs and smaller footprints compared to traditional systems. These developments aim to make electron beam processing economically viable for a broader range of applications and production volumes [18, 19].

Compact accelerators in the energy range of 200-300 keV have been designed for specific industrial and medical applications. The reduction in system size and cost, combined with improved reliability and ease of operation, supports wider adoption of electron beam surface treatment technology. Continued development of compact, efficient accelerator designs remains an active area of research [18, 19, 47].

COMPARATIVE ANALYSIS WITH OTHER SURFACE TREATMENT METHODS

Comparison with Laser Beam Hardening

Electron beam and laser beam hardening share many similarities as high-energy beam surface treatment methods, yet exhibit important differences. Both technologies enable precise, localized surface hardening with minimal bulk heating and distortion. However, electron beams offer several advantages including higher energy absorption efficiency, larger processing areas, and deeper penetration depths [1, 20, 29, 48, 52].

For submicron bainitic steels used in gear production, comparative studies have evaluated electron beam hardening against laser beam hardening to identify optimal surface hardening methods. Electron beam processing typically achieves more uniform energy distribution over larger areas due to the ease of beam deflection and scanning. The vacuum requirement for electron beam processing represents a disadvantage compared to laser processing, which can be performed in atmospheric conditions [5, 20, 48, 52].

The energy absorption characteristics differ significantly between the two technologies. Electron beams exhibit high absorption depths and are less affected by surface reflectivity compared to laser beams. This characteristic makes electron beam processing more suitable for highly reflective materials such as aluminum alloys [48, 52]. However, laser systems offer greater flexibility in terms of beam delivery and can more easily treat large structures that cannot fit in vacuum chambers [48, 52].

Comparison with Conventional Heat Treatment

Electron beam surface hardening offers substantial advantages over conventional bulk heat treatment processes. The localized energy deposition enables surface hardening without heating the entire component, dramatically reducing thermal distortion. Components treated with electron beam hardening typically exhibit dimensional changes an order of magnitude smaller than those subjected to conventional through-hardening [5, 6, 46].

The elimination of external quenching media and subsequent tempering operations simplifies the process and reduces cycle time. Conventional heat treatment requires careful control of furnace atmosphere, quenching conditions, and tempering parameters, each introducing potential sources of variation and distortion. Electron beam hardening achieves the desired surface properties in a single, rapid processing step [2, 5, 36, 53, 54, 55, 56, 57, 58].

The extremely high heating rates achievable with electron beams produce finer microstructures and more uniform property distributions compared to conventional heating methods. However, conventional heat treatment can achieve greater case depths and may be more economical for simple geometries and high-volume production of lower-value components. The choice between electron beam and conventional heat treatment depends on component geometry, required property distribution, production volume, and economic considerations [2, 5, 14, 53, 54, 55, 56, 57, 58].

Comparison with Induction Hardening

Induction hardening represents another widely used surface hardening technology that competes with electron beam processing in certain applications. Both methods enable localized surface hardening with rapid heating rates. Induction hardening offers the advantages of atmospheric processing, lower capital costs, and well-established industrial practice.

Electron beam hardening provides superior control over the energy distribution and can treat complex geometries more effectively than induction hardening. The depth and uniformity of hardening achievable with electron beams often exceeds that of induction processing. However, induction hardening can be more economical for simple geometries such as cylindrical shafts and can achieve greater case depths.

The heating mechanism differs fundamentally between the two technologies. Induction heating relies on electromagnetic induction (Figure 10) and is limited to electrically conductive materials, while electron beam heating works effectively on all materials.

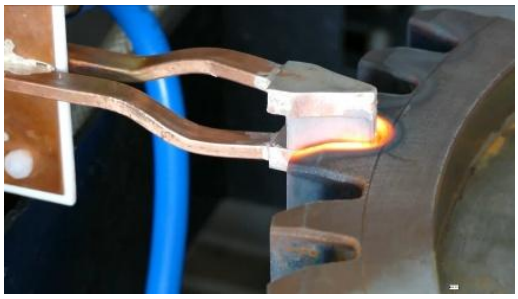


Fig. 9 Induction hardening of gear wheel

Alt text: *Illustration showing the induction hardening process applied to a gear wheel, highlighting localized surface heating and hardening of the gear teeth.*

The vacuum requirement and higher capital cost of electron beam systems limit their application primarily to high-value components where the superior control and property enhancement justify the additional cost [1, 2, 5, 14, 27, 35, 56, 57, 58].

Comparison with Ion Beam Treatment

Ion beam surface modification represents an alternative high-energy beam technology with distinct characteristics compared to electron beam processing. Both technologies can achieve surface hardening, wear resistance improvement, and microstructural refinement. Ion beam treatment offers the advantage of simultaneous surface modification and implantation of beneficial elements [21, 22].

Electron beam processing typically achieves higher processing rates and treats larger areas more efficiently than ion beam methods. The energy absorption and penetration characteristics differ significantly, with electron beams generally achieving deeper modification. Ion beam treatment excels in applications requiring precise control of surface composition and shallow modification depths [1, 21].

For titanium alloys, both electron beam and ion beam treatments have been extensively studied, with each offering distinct advantages. Electron beam treatment demonstrates enhanced thermal effects and higher processing efficiency, while ion beam treatment provides superior control over surface composition. The choice between technologies depends on the specific application requirements and desired property modifications [21].

Comparison with Plasma-Based Methods

Plasma-based surface treatment methods, including plasma nitriding and pulsed plasma processing, offer alternative approaches to surface modification. Plasma nitriding can be effectively combined with electron beam hardening to achieve synergistic property enhancements. Pulsed plasma sources can achieve significant increases in surface hardness and wear resistance, with some studies reporting 4-10 fold improvements similar to electron beam treatmen [11, 22, 35, 52].

Electron beam processing offers advantages in terms of processing speed, energy efficiency, and precise control over the thermal cycle. The vacuum environment required for electron beam processing is similar to that needed for many plasma processes, reducing the relative disadvantage. Plasma-based methods excel in applications requiring surface chemical modification, such as nitriding, while electron beam processing focuses primarily on thermal modification [11, 22].

The combination of electron beam treatment with plasma-based methods represents a promising hybrid approach. Electron beam hardening followed by plasma nitriding produces property combinations unattainable with either process alone. This synergistic approach leverages the strengths of both technologies to achieve optimized surface properties [11, 22, 35, 36].

FUTURE TRENDS AND RESEARCH DIRECTIONS

Integration with Industry 4.0

The integration of electron beam surface treatment with Industry 4.0 concepts represents a significant future trend. The incorporation of advanced sensors, real-time monitoring, and data analytics will enable adaptive process control and predictive maintenance. Digital twin technology can provide virtual process development and optimization, reducing time and cost for new application development [6, 11].

The connectivity of electron beam systems with enterprise manufacturing execution systems will enable seamless integration into smart factories. Real-time quality monitoring and feedback control will improve process consistency and reduce scrap rates. The application of machine learning algorithms to process optimization promises to unlock new capabilities and expand the application range of electron beam technology [11].

Expansion to New Material Systems

Research continues on expanding electron beam surface treatment to new material systems beyond traditional steels and titanium alloys. Magnesium alloys, aluminum alloys, and advanced high-strength steels represent important targets for future development. The treatment of composite materials and multi-material assemblies presents both challenges and opportunities [1, 6, 33, 49, 59].

Additive manufacturing materials, including those produced by electron beam melting, represent an emerging application area. The combination of additive manufacturing with electron beam surface treatment could enable production of components with optimized bulk and surface properties. Research on electron beam treatment of advanced ceramics and intermetallic compounds may open new application fields [1, 11, 21].

Hybrid and Multi-Process Technologies

The development of hybrid technologies combining electron beam processing with multiple complementary treatments represents a key research direction [20, 21, 23]. Beyond the established combinations with nitriding and PVD coatings, new hybrid processes incorporating additive manufacturing, laser processing, and advanced coating technologies are under investigation [11, 28, 29, 31, 49, 60].

Multi-step processes that sequentially apply different surface treatments to achieve complex property gradients and multi-functional surfaces show particular promise. The optimization of process sequences and parameters for hybrid technologies requires sophisticated modeling and experimental validation. Research on the fundamental mechanisms of interaction between different surface treatments will guide development of optimized hybrid processes [28, 29].

Micro and Nano-Scale Surface Engineering

The application of electron beam technology to micro and nano-scale surface engineering represents an emerging research frontier. High-energy density beams enable micro- and nano-texturing of surfaces through rapid melting and solidification. The formation of nanostructured surface layers with enhanced properties offers potential for advanced applications [1, 20, 22].

Research on controlling the formation of specific nanostructures and understanding their effects on material properties continues to advance. The development of electron beam processing techniques specifically designed for nano-scale modification may enable new applications in electronics, photonics, and biomedical devices. The combination of electron beam processing with other nano-fabrication techniques could enable production of complex, multi-functional nanostructured surfaces [1, 13, 20, 22].

Environmental and Sustainability Considerations

Future development of electron beam technology will increasingly focus on environmental sustainability and energy efficiency. The inherently clean nature of electron beam processing, with no chemical waste or emissions, positions it favorably for environmentally conscious manufacturing. Research on reducing energy consumption and improving process efficiency will enhance the sustainability profile of the technology [6, 18, 19, 20].

The development of more efficient accelerators and power supplies will reduce the energy footprint of electron beam processing. Life cycle assessment studies comparing electron beam treatment with alternative technologies will provide quantitative data on environmental impacts. The ability of electron beam processing to extend component life and reduce material consumption contributes to overall sustainability goals [6, 18, 19, 20].

From a broader sustainability perspective, extending the service life of components operating under severe wear conditions is becoming increasingly important in the context of eco-design requirements and climate policies. Reducing the frequency of component replacement and refurbishment decreases material consumption, energy demand throughout the product life cycle, and the overall environmental footprint of industrial systems. This aspect is particularly important for mining machinery components

exposed to intensive abrasive, erosive, and tribocorrosive wear. Improving their durability through advanced surface engineering solutions may significantly reduce the demand for replacement parts, supporting both resource efficiency and environmental sustainability objectives [61, 62, 63, 64].

Widening Industrial Adoption

Expanding the industrial adoption of electron beam surface treatment beyond current high-value applications represents an important goal. The development of lower-cost, more compact systems will make the technology accessible to a broader range of manufacturers. Improved understanding of process-structure-property relationships will enable more confident application to new components and materials [6, 14, 18, 30].

The establishment of industry standards and best practices for electron beam surface treatment will support wider adoption. Training programs and knowledge transfer initiatives will develop the skilled workforce needed to implement and operate electron beam systems. Demonstration projects showcasing the benefits of electron beam technology in new application areas will drive market expansion [6, 14, 30].

CONCLUSIONS

Electron beam hardening and surface modification is a mature and versatile technology for improving surface properties in production engineering. Precise, localized deposition of high-energy electron beams enables rapid thermal cycles, refined microstructures, and enhanced mechanical properties, while offering minimal thermal distortion, high productivity, precise process control, environmental benefits, and compatibility with complementary surface treatments.

The process involves heating rates of up to (10^9) K/s followed by self-quenching through heat conduction into the cold substrate. This can produce fine-grained martensitic or bainitic structures, nanoscale grains, high dislocation densities, and non-equilibrium phases. Reported improvements include 2-3-fold increases in hardness, 4-10-fold improvements in wear resistance, and 2.2-3.5-fold increases in fatigue life across various material systems.

Industrial applications include the automotive, aerospace, tooling, and medical sectors, particularly for gears, camshafts, turbine blades, cutting tools, and implants. Industrial-scale production rates exceeding 3,500 parts per hour have been achieved for automotive components. Selective treatment of critical regions while retaining bulk material properties enables effective optimization of component performance and durability.

Recent developments include hybrid processes combining electron beam treatment with nitriding, PVD coatings, and other surface technologies, as well as pulsed and large-area electron beam processing. Compact and lower-cost accelerators may further broaden industrial accessibility. Compared with laser hardening, conventional heat treatment, induction hardening, ion beam treatment, and plasma-based methods, electron beam processing is particularly advantageous where precise control, low distortion, and strong surface-property enhancement are required, although technology selection remains dependent on application requirements, geometry, production volume, and economic factors.

Future development is expected to focus on Industry 4.0 integration, new material systems, advanced hybrid processes, micro- and nanoscale surface engineering, and improved sustainability. Continued cost reduction, process optimization, and expansion into new applications are likely to support wider industrial adoption. Overall, electron beam hardening and surface modification remains an important enabling technology for producing high-performance components with enhanced surface properties and reduced distortion.

REFERENCES

[1]. Yu. F. Ivanov et al. (2020). Prospects for the Application of Surface Treatment of Alloys by Electron Beams in State-of-the-Art Technologies. *Progress in Physics of Metals*, 21 (3), pp. 345-362. DOI: 10.15407/ufm.21.03.345.

[2]. Zenker, R. (1996). Electron beam surface treatment: industrial application and prospects. *Surface Engineering*, 12(4), pp. 296-297. DOI: 10.1179/sur.1996.12.4.296.

[3]. Zenker, R. (1992). Electron Beam Surface Modification State of the Art (Review). *Materials Science Forum*, 102-104, pp. 459-476. DOI: 10.4028/www.scientific.net/msf.102-104.459.

[4]. Pobol. I.L. (1990). Modification of metals and alloys by electron beam treatment (review). *Metal Science and Heat Treatment*, 32, pp. 520-527, DOI: 10.1007/BF00700325.

[5]. Śliwiński P., et al. (2022) Electron Beam Surface Hardening. *Bulletin of the Welding Institute*, 66(1), pp. 7-20. DOI: 10.17729/ebis.2022.1/1.

[6]. Zenker, R. (2009). Modern thermal electron beam processes – research results and industrial application. *La Metallurgia Italiana*, 101(4).

[7]. Zenker, R., et al. (2013). Electron beam surface hardening. In J. Dossett & G. E. Totten (Eds.), ASM Handbook, Volume 4A: Steel Heat Treating Fundamentals and Processes pp. 687-698. ASM International. DOI: 10.31399/ASM.HB.V04A.A0005817

[8]. DVS. (2013). DVS Technical Codes on Electron Beam Welding (English ed., Vol. 8). DVS Media. ISBN: 978-3-87155-244-1.

[9]. Schulze, K.-R. (2012). Electron Beam Technologies: Compact Knowledge. DVS Media. ISBN: 978-3-87155-227-4.

[10]. Pilarczyk, J., et al. (2015). Wytwarzanie powłok i modyfikacja powierzchni przy użyciu wiązki elektronów w spawalnictwie. *Przegląd Spawalnictwa*, 87(9), pp. 38-44. DOI: 10.26628/wtr.v87i9.449

[11]. Valkov, S., et al. (2020). Electron-beam surface treatment of metals and alloys: Techniques and trends. *Metals*, 10(9), 1219. DOI: 10.3390/met10091219.

[12]. Rotshtein, V. P., et al. (2004). Surface modification and alloying of metallic materials with low-energy high-current electron beams. *Surface and Coatings Technology*, 180-181, pp. 377-381. DOI: 10.1016/j.surfcoat.2003.10.085

[13]. Proskurovsky, D.I., et al. (2000). Physical foundations for surface treatment of materials with low-energy, high-current electron beams. *Surface and Coatings Technology*, 125(1-3), pp. 49-56. DOI: 10.1016/S0257-8972(99)00604-0.

[14]. Zenker, R., et al. (2011). IFHTSE Global 21: Heat treatment and surface engineering in the twenty-first century. Part 15 – Progress in surface heat treatment using electron beam surface hardening. *International Heat Treatment and Surface Engineering*, 5(1), pp. 38-43.

[15]. Śliwiński, P., et al. (2025). Wpływ hartowania elektronowego na właściwości tribologiczne stali w różnych stanach dostawy. *Materials Science and Welding Technologies*, 69(2). DOI: 10.32730/mswt.2025.69.2.4.

[16]. Pilarczyk, J., et al. (2015). Electron beam welding. Welding Technology Review, 87(10).

[17]. Węglowski, M.S., et al. (2021). Electron beam melting of thermally sprayed layers – overview. *Bulletin of the Welding Institute*, 65(3), pp. 7-19.

[18]. Scharf, W., et al. (1999). Electron accelerators for industrial processing – a review. *AIP Conference Proceedings*, 475, pp. 1105-1112. DOI: 10.1063/1.59300

[19]. Ribton, C. (1999). Intelligent power supplies for electron beam welding at 300 kV and 150 kW. In IEE Colloquium on Power Electronics for Demanding Applications (Ref. No. 1999/059, Paper 4/1-4/7). IET.

[20]. Śliwiński, P., et al. (2025). Characteristics of the Novel Electron Beam Hardening Technology for Submicron Bainitic Steels in the Context of Its Application in the Production of Gears and Comparison with the Competitive Laser Beam Technology. Coatings, 15(11), 1321. DOI: 10.3390/coatings15111321.

[21]. Gudala, M., et al. (2023). Effect of ion and electron beam treatments on titanium and its alloys: A critical review on structure, properties, and applications. *Materials Today Communications*, 37, 107453.

[22]. Surla, K., et al. (2011). High-energy density beams and plasmas for micro- and nano-texturing of surfaces by rapid melting and solidification. *Journal of Physics D: Applied Physics*, 44(17), 174026. DOI: 10.1088/0022-3727/44/17/174026.

[23]. Matsui, K., et al. (1990). Electron beam hardening. International Journal of Materials and Product Technology, 5(3), pp. 321-330. DOI: 10.1504/IJMPT.1990.036617.

[24]. Storch, W., et al. (1988). Electron beam hardening for the regeneration of turbine blades. *Welding International*, 2(12), pp. 1127-1130.
[25]. Mueller, G., et al. (2002). Application of pulsed electron beams for improvement of material surface properties. *AIP Conference Proceedings*, 650, pp. 641-644. DOI: 10.1063/1.1530864.
[26]. Goriainov, V., et al. (2018). Human skeletal stem cell response to multiscale topography induced by large area electron beam irradiation surface treatment. *Frontiers in Bioengineering and Biotechnology*, 6, 91. DOI: 10.3389/fbioe.2018.00091.
[27]. Vesković, S. (2022). Condition, development, potential and application of electronic treatment. *International Journal of Electrical Engineering and Computing*, 6(2), pp. 75-88. DOI: 10.7251/ijeec2202075k.
[28]. Matlák, J., et al. (2018). Properties of electron beam hardened layers made by different beam deflection. *Manufacturing Technology*, 18(2), pp. 279-284. DOI: 10.21062/ujep/96.2018/a/1213-2489/MT/18/2/279.
[29]. Petrov, P. (2010). Optimisation of carbon steel electron-beam hardening. *Journal of Physics: Conference Series*, 223, 012029. DOI: 10.1088/1742-6596/223/1/012029.
[30]. Friedel, K.P., et al. (1996). A systematic method for optimising the electron beam hardening process. Vacuum, 47(11), pp. 1317-1324.
[31]. Schiller, S., et al. (1989). Thermal surface modification by electron beam high-speed scanning. *Surface and Coatings Technology*, pp. 39-40 (Part 1), pp. 369-380. DOI: 10.1016/S0257-8972(89)80013-1.
[32]. Fu, Y., et al. (2017). Surface hardening of 30CrMnSiA steel using continuous electron beam. Nuclear Instruments and Methods in Physics Research Section B: *Beam Interactions with Materials and Atoms*, 410, pp. 207-214.
[33]. Angelov, V., et al. (2019). Selective electron beam surface alloying of aluminium with TiCN nanoparticles. Nuclear Instruments and Methods in Physics Research Section B: Beam *Interactions with Materials and Atoms*, 440, pp. 88-94.
[34]. Panin, A., et al. (2019). Continuous electron beam post-treatment of EBF³-fabricated Ti-6Al-4V parts. *Metals*, 9(6), 699. DOI: 10.3390/met9060699.
[35]. Zenker, R. (2009). Electron meets nitrogen: Combination of electron beam hardening and nitriding. *International Heat Treatment and Surface Engineering*, 3(4), pp. 171-175.
[36]. Zenker, R., et al. (2007). Combination of high energy beam processing with thermochemical treatment and hard protective coating: State of the art. *International Heat Treatment and Surface Engineering*, 1(4), pp. 159-164.
[37]. Zhao, T., et al. (2009). Research development of electron beam surface treatment. *Heat Treatment of Metals*, 34(5), pp. 22-26.
[38]. Song, R.G., et al. (2003). Electron beam surface treatment. Part I: Surface hardening of AISI D3 tool steel. *Vacuum*, 69(3), pp. 513-516.
[39]. Dimitrov, D., et al. (1998). Electron beam hardening of ion nitrided layers. *Vacuum*, 49(3), pp. 239-246.
[40]. Yang, J., et al. (2020). Effect of different scanning modes of a multi-beam system on the surface properties of continuous electron beam treated 40CrMn steel. Nuclear Instruments and Methods in Physics Research Section B: *Beam Interactions with Materials and Atoms*, 467, pp. 102-107.
[41]. Wang, D., et al. (2018). Surface modification of 5CrMnMo steel with continuous scanning electron beam process. *Vacuum*, 149, pp. 118-123.
[42]. Hu, W., et al. (2020). Experimental investigations of nanosecond-pulse electron beam profile for metal surface treatments. *In Procedia CIRP*, 95, pp. 966-971.
[43]. Fu, Y., et al. (2020). Microstructure modification of AISI 1045 steel induced by high-current pulsed pseudospark electron beam. *Procedia CIRP*, 95, pp. 972-975.
[44]. Fu, Y., et al. (2018). Surface modification of AISI 1045 steel by pseudospark-based pulsed electron beam. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 434, pp. 88-92.
[45]. Zou, J.X., et al. (2007). Microstructures and phase formations in the surface layer of an AISI D2 steel treated with pulsed electron beam. *Journal of Alloys and Compounds*, 434-435, pp. 707-709.
[46]. Zenker, R., et al. (2007). Hybrid technology hard coating – Electron beam surface hardening. *Surface and Coatings Technology*, 202 (4-7), pp. 820-823. DOI: 10.1016/j.surfcoat.2007.05.089.
[47]. Ozer, S. (2017). Electron beam irradiation processing for industrial and medical applications. EPJ Web of Conferences, 154, 01019. DOI: 10.1051/epjconf/201715401019..

[48]. Kear, B.H., et al. (1987). Surface modification by rapid solidification laser and electron beam processing. In T.S. Sudarshan & J.F. Braza (Eds.), Surface Modification Technologies: An Engineers' Guide pp. 217-236. Springer, Boston, MA. DOI: 10.1007/978-1-4615-9501-4_12.
[49]. Śliwiński, P., et al. (2024). Electron beam hardening of nanobainitic steel. Surface Engineering, 40(3), Article DOI: 10.1177/02670844241249728.
[50]. https://kindle-tech.com/faqs/what-are-the-applications-of-electron-beam-hardening
[51]. https://www.pro-beam.com/en/contractmanufacturing/hardening/
[52]. Valkov, S., et al. (2018). Surface manufacturing of materials by high energy fluxes. In M. Aliofkhazraei (Ed.), Surface Engineering and Functional Coatings. *IntechOpen*. DOI: 10.5772/intechopen.79874.
[53]. Burakowski, T., et al. (1995). *Metal Surface Engineering*. Warsaw: Wydawnictwa Naukowo-Techniczne.
[54]. Dobrzański, L.A. (2006). *Engineering Materials and Material Design: Fundamentals of Materials Science and Metallurgy*. Warsaw: Wydawnictwa Naukowo-Techniczne.
[55]. Nowotyńska, I., et al. (2014). Selected methods of surface treatment of metal forming tools. *Logistyka*, 6, pp. 8670-8679.
[56]. Dobrzański, L.A., et al. (2011). Surface Treatment of Engineering Materials. Open Access Library, 5.
[57]. Pawłowski, B. (2005). *Heat and thermochemical treatment of steel*. In J. Pacyna (Ed.), Metallurgy: Selected Issues pp. 175-202. Kraków: AGH University of Science and Technology Press.
[58]. Jankowski, T., et al. (1995). *Hardening and tempering of carbon steels*. In J. Hucińska (Ed.), Metallurgy: Materials for Laboratory Exercises pp. 107-129. Gdańsk: Gdańsk University of Technology Press.
[59]. Stachowiak, A., et al. (2021). Comparative tribocorrosion tests of 30CrMo12 cast steel and ADI spheroidal cast iron. *Tribology International*, 153, 106763. DOI: 10.1016/j.triboint.2020.106763.
[60]. Myszka, D., et al. (2014). Manufacture of toothed elements in nanoausferritic ductile iron. *Archives of Metallurgy and Materials*, 59(3), pp. 1217-1221. DOI: 10.2478/amm-2014-0211.
[61]. Myszka, D., et al. (2015). Effect of phenomena accompanying wear in dry corundum abrasive on the properties and microstructure of austempered ductile iron with different chemical composition. Archives of Metallurgy and Materials, 60(1), pp. 483-490. DOI: 10.1515/amm-2015-0078.
[62]. Wieczorek, A.N. (2017). Operation-oriented studies on wear properties of surface-hardened alloy cast steels used in mining in the conditions of the combined action of dynamic forces and an abrasive material. *Archives of Metallurgy and Materials*, 62(4), pp. 2381-2389. DOI: 10.1515/amm-2017-0351.
[63]. Wieczorek, A.N. (2014). The role of operational factors in shaping of wear properties of alloyed austempered ductile iron. Part I. Experimental studies abrasive wear of austempered ductile iron (ADI) in the presence of loose quartz abrasive. *Archives of Metallurgy and Materials*, 59(4), pp. 1653-1662. DOI: 10.2478/amm-2014-0281.
[64]. Wieczorek, A.N. (2014). The role of operational factors in shaping of wear properties of alloyed austempered ductile iron. Part II. An assessment of the cumulative effect of abrasives processes and the dynamic activity on the wear property of ausferritic ductile iron. *Archives of Metallurgy and Materials*, 59(4), pp. 1663-1671. DOI: 10.2478/amm-2014-0282.

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