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Application of Electrolytic Plasma Process in Surface Improvement of Metals: A Review

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Abstract: Electrolytic plasma heat treatment is becoming a popular heat treatment process in the field of surface engineering. In this paper, research data from different research works have been analyzed. The basic mechanism of the electrolytic plasma heat treatment process is discussed along with its scope in the industry. The review is done to extend the research work of this novel process and its scope from the industrial point of view. The study will explore the electrolytic plasma process to target industrial benefits and to attract the researchers for improving the various aspects of the process. Different types of electrolytic plasma treatment have been discussed to show the capabilities of the process for improving surface properties of different metals. It is found that the treatment is less time consuming, economical, eco-friendly, and dynamic as compared to the existing heat treatment processes. Its dynamic ability makes it possible to perform carburizing, nitriding, coating, cleaning, polishing, and hardening operations in the same experimental setup with little modification.

Keywords: Plasma Electrolytic Treatment (PET); Electrolytic Plasma Heat Treatment(EPHT).

1. Introduction

Surface improvement of metals is made to increase working life, improve the performance, and giving an aesthetic look to the metallic components. Surface properties of steel, such as wear resistance, hardness, and corrosion resistance, can be improved by surface modification processes that involved hardening, nitriding, carburizing, and nitrocarburizing. Similarly, a protective layer of a particular material can also be introducing on the surface of metals.

In the industry where steel is used in the manufacturing of every component, surface improvement plays a vital role in introducing desired mechanical properties in the steel. Press tool shops, automobile companies, press part manufacturers, aerospace industry, shipbuilding industry, Biomedical equipment manufacturer, weapon manufacturing industry are some of the areas where steel is a common metal, and hence improving the properties of steel by different techniques becomes important. Traditionally only heating and cooling of steel was the most common method of surface treatment that exist as time passed, different surface treatments evolved. Conventional heat treatment consists of heating metal in the furnace and cooling in air, water, or oil. There are also other heat treatment processes used to improve surface properties of steel such as nitriding, carburizing, vacuum heat treatment, cryogenic heat treatment, laser heat treatment, ion beam heat treatment, etc. All these processes require high-cost setup, time of treatment is more, some processes are not eco-friendly and some are having bulky apparatus. The electrolytic plasma treatment is a novel method to encounter all these disadvantages. It is proving that it can successfully improve desired mechanical properties with much less time about few minutes as compared to traditional heat treatment processes, which require hrs and days. Also, very low-cost equipment is required, and the process is eco-friendly.

The purpose of this review is to study and focus on the various aspects of a novel method of heat treatment known as Plasma Electrolytic treatment for identifying its scope and exploring areas of challenges in it.

It is proved that electrolytic plasma treatment can successfully improve wear resistance and corrosion resistance of steel. Also, a considerable depth of hardness can be achieved in the case of tool steel to increase tool life. Single setup of an experiment can perform a different type of surface treatment such as hardening, nitriding, carbonitriding, plating, polishing, and cleaning. However, though the process is carried out for the different type of steel as well as aluminum, there is no standardized material-wise heat treatment cycle have been established till the date. Also, as the plasma formation is an instantaneous process and occurs within a fraction of seconds, it becomes difficult to stabilize the input process parameters to gain the output parameters as per our need. Due to its present technical challenges, the process is still in the development phase and not commercialized worldwide, like other processes such as cryogenics and vacuum heat treatment. Cathodic electrolytic plasma hardening of cast iron based camshaft has been carried out, and it was observed that the hardness of cast iron based automotive camshaft increased to 60HRC with 5mm depth of hardness [20]. A 20µm thick layer of hardness around 460HV has achieved by plasma electrolytic nitriding at 850°C only for 5min in the case of Titanium alloy [23]. The highest microhardness of 950HV is achieved by Plasma Electrolytic Nitriding, and also surface roughness was reduced from 4.5 to 1.9 µm [40].

Anode plasma electrolytic nitro hardening in 15 wt.% NH_4Cl as an electrolyte has been successfully carried out, and microhardness of about 1060HV was obtained within 5min at a temperature of 750°C [49]. Low carbon steel, when treated with plasma electrolytic nitrocarburizing at 850°C, shown an increase in hardness up to 750HV with 0.2mm depth of hardness. It was proposed that anode plasma electrolytic nitrocarburizing increases wear resistance and decrease surface roughness of low carbon steel [50]. Plasma electrolytic nitriding carried out with plasma electrolytic hardening has achieved a combination of high hardness and wear resistance. The hardness of 56-62 HRC was obtained by plasma electrolytic hardening, and after that, the corrosion resistance was improved by nitriding. Both processes were carried out in the same electrolyte and same setup [51]. Cathodic electrolytic plasma hardening has also been carried out, and it was found that the hardness of cast iron based automotive camshaft increased to 60HRC with 5mm depth of hardness [20]. High surface finishing of a 38KH2N2MA Structural alloy steel was achieved by using a combination of Electrolytic Discharge Machining and Plasma Electrolytic Polishing. It was concluded that the surface roughness reduced by a factor of 5 within a 5min anodic plasma electrolytic process [52]. A coating thickness of 80µm was successfully achieved by electrolytic plasma oxidation. The specimen used was VT6 titanium alloy and coating formed was of Titanium oxide [53]. Electrolytic plasma hardening of Banding steel has increases microhardness by 2.4 times of substrate within 4s of heating [55]. The phase composition of electrolytic plasma carbonitrided steel specimen has been studied by Transmission Electron Microscopy, and it was observed that martensite, cementite, and carbonitrides lamellas were successfully formed on the steel surface [56].

The electrolytic plasma process has been studied by the direct current method and pulse current method. It was proved that for surface hardening of AISI 1050 steel, the pulse current method requires less voltage and time as compared to the direct current method [41]. The corrosion resistance of carbonyl iron powder was increased by depositing the SiO_2layer on the carbonyl surface with the help of plasma electrolytic deposition [54]. Corrosion behavior of SS304 also been studied in which ball-milled specimens were first annealed and then treated with Electrolytic Plasma Process. It was found that the corrosion resistance improved significantly [101]. The deposition rate of oxide coating on Magnesium alloy increases when the Electrolytic Plasma Process was used in pulse polarization mode [70]. Sequential coating and polishing are also possible by using the electrolytic plasma process, which makes this process dynamic and multifunctional [84]. Boriding of structural steel and Titanium alloys was done by using the electrolytic plasma process. It was observed that both wear resistance and corrosion resistance improved significantly in the case of structural steel as well as Titanium alloy [87].

The plasma electrolytic Oxidation process has been used for the coating of aluminum alloy, nickel alloy, titanium alloy, carbon fiber, and many more metals. Machining of aluminum alloy coated with ceramic oxide by electrolytic plasma oxidation process also studied, and it is shown that wear resistance property of aluminum alloy increases and abrasive polishing suggested for final machining of such component [94]. Ti alloy used for bio-implant application shows an increase in wear resistance and corrosion resistance after treated with plasma electrolytic oxidation, and also weldability in terms of contact angle also improved [104].

This electrolytic plasma process is an electrolysis process that is carried out at high voltage to create plasma for heating the metal at high temperatures. A combination of plasma and electrolysis has achieved a novel contribution in the field of surface heat treatment technologies, as shown in figure 1.

The process aspects of the technology have been explained as follows:

1.1. Plasma.

There are three states of matter solid, liquid, and gases. Nevertheless, there exists a fourth state also, which is beyond the gaseous state, and it is called plasma. If heat is applied to a liquid, it gets vaporized at high temperatures, and liquid state changes to a gaseous state. When this gaseous is further heated, the free electrons separate from particles, and positive ions with free electrons are formed. These free electrons conduct electricity. The plasma formation phase is indicated by a glow discharge for a very short duration of time, and this glow can heat the metal up to 2000°C [1]. This heat is utilized for the surface modification of metals.

1.2. Electrolysis.

For the surface modification of steel, it may require to deposit carbon or nitrogen particles on the surface of steel with the help of an external agent. This can be done by electrolysis in which electrode is deposited with carbon or nitrogen atoms by supplying high voltage across the electrode dipped in a particular electrolyte. This electrolyte plays an important role in conducting electricity. The combination of plasma and electrolysis can be used to carry out a novel method of surface treatment, which is called as Electrolytic Plasma Surface Treatment.

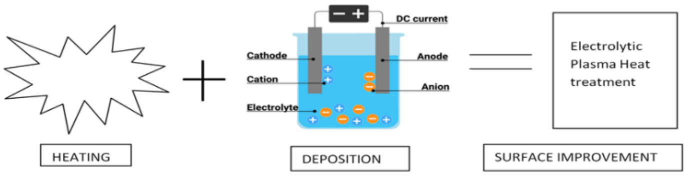

Figure 1. The combination of electrolysis and plasma improves surface properties.

1.3. Electrolytic Plasma Process.

In the conventional electrolysis process, the voltage applied across the electrodes is very less as compared to the electrolytic plasma technique in which the voltage is around 200V to 400V. A DC power supply is used to apply a high voltage across the cathode and anode. The workpiece may be a cathode or may be an anode. If cathode works as a work piece, then it is cathodic plasma electrolytic heat treatment, and if anode works as a specimen, then that will be an anodic plasma electrolytic heat-treatment process. As the application of electric potential is very large as compared to conventional electrolysis, the gas liberation density at the surface of the electrode is very much and which leads to continuous gas envelope around the electrode along with an electric discharge. This electric discharge is responsible for extensive heating of the specimen above its recrystallization temperature within a fraction of seconds. The specimen can then be quenched in the same electrolyte by disconnecting the power supply. Various research works show that after the plasma electrolytic heat treatment, the surface properties of steel improved considerably.

The process can be categorized into four main phases, which begins with the formation of vapor around the electrode being treated. Figure 2 shows stages of the electrolytic plasma process in which, after supplying power, the temperature goes on increasing and reaches the highest point when plasma formation occurs. After plasma glows, the power supply is disconnected and electrode quenched in the same electrolyte.

The author studied the relation between current and voltage for AISI 1080 high carbon steel to demonstrate plasma formation in the EPHT process. The spark ignition phase is followed by the continuous plasma envelope which is supposed to be a treatment phase for the metals. Gas liberation phase involves the highest peak of current, and after that increase in voltage, causes an increase in accumulation of charges, and spark ignition occurs. Spark ignition results in heating of electrolyte around the cathode and continuous vapor envelop formed, which results in resistance to the current flow [1].

The cathode can be cooled in the same electrolyte after disconnecting the voltage supply for quenching purposes, which is the requirement of the hardening process. Carbon and nitrogen atoms can be imparted on the surface of electrolytes in the continuous plasma envelope phase.

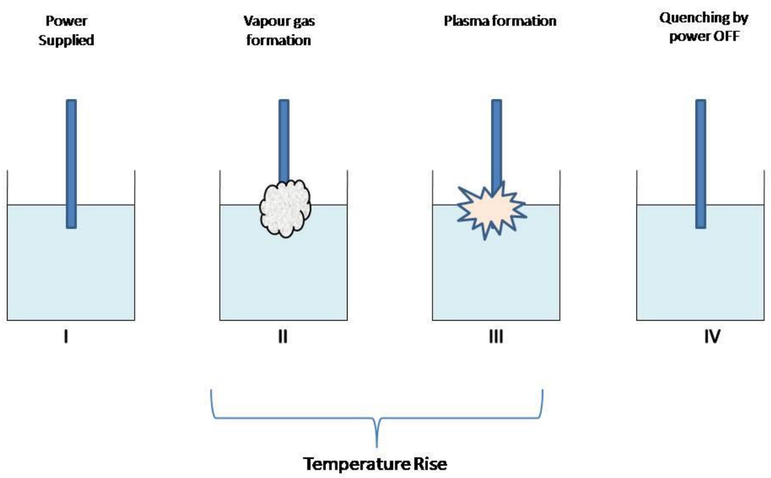

Figure 2. Stages in Electrolytic plasma heat treatment: I) Power on II) Vapour formation III) Plasma formation IV) Quenching

2. Surface morphology

2.1. Alternate heating and cooling method.

When AISI 4140 was treated with electrolytic plasma thermo cyclic treatment, the stereo microscopic view of the material cross-section clearly indicated the hardened zone and unaffected zone [2]. In this technique, a higher of 300-320 V is applied for a few seconds, and then a lower voltage of 230-250 V applied. Alternate high and low voltage application results in heating and cooling, which results in the development of the high thicked hardened layer within just 42s. In this way, in a very shorter time, the higher thickness can be obtained by optimizing the process parameters.

The microstructure of the treated specimen depends on heating and cooling cycles in electrolytic plasma hardening. The lower number of cycles results in two layers, namely the hardened zone and transition zone on base material [33]. Higher number of cycle results in three zones namely remelted zone, hardened zone and transition zone on base material. The depth of the hardness increases with the number of cycles. However, there is a requirement of an optimum condition.

2.2. Deposition methods.

The deposition of carbon, nitrogen, boron on the surface of steel has been successfully carried out with electrolytic plasma heat treatment [34, 35]. After treating Q235 steel with electrolytic plasma carbonitriding, it was found that the highest thickness of 75 microns was obtained within just 75s with hardness value up to the 750HV. When the relation between time and hardness was studied, it was observed that for a higher time, the depth of hardness is higher hardness profile was wider than lower treatment time profile. At higher treatment time, which was more than 75s, the quality of the layer was deteriorated due to the reticular pattern of the carbide layer [34].

Boronizing of different steel grades steel was carried out by electrolytic plasma process, and it was observed that steel containing more percentage Cr can exhibit more boron diffusion and highe thickness of the boride layer was developed [35]. The maximum hardness for medium carbon steel was obtained up to 1200HV, which was less as compared to the traditional boronizing process, but the thickness of the boride layer was higher and fabricated in a short duration. Tool steel is the backbone material of advanced manufacturing industries, and different technologies have been developing to increase the surface properties of tool steel. Plasma electrolytic nitriding of tool steel has been carried out by using ammonium nitrate and ammonium chloride solution [36]. When tool steel treated with Plasma Electrolytic Nitriding (PEN) it was found that maximum microhardness was obtained 1280HV with improvement in corrosion resistance.

Commercial grade austenitic stainless steel developed 20-60 micron nitride layer when treated by plasma electrolytic nitriding during 20-60 min in the temperature range of 375 to 480 °C with manual control of temperature. It was proposed that the process will be more efficient after more accurate process control parameters like the temperature of the sample and composition of electrolyte [37].

2.3. Surface coating and polishing.

Plasma electrolytic oxidation was used to fabricate oxide film on the surface of a Titanium alloy by using Ac power source. In this work, PEO film was produced by using a silicate electrolyte. The film produced is having a good combination of thickness, hardness, wear-resistance, and adhesion. The type of electrolyte determines the corrosion resistance property and friction coefficient based on the process of chemical reaction stability of the coating [38]. Alumina coating technique is very effective for improving hardness, wear resistance, and corrosion resistance of steel and aluminum alloys. Plasma electrolysis has been successfully implemented on BS Al 6082 for Al_2O_3 coating. XRD and TEM analyses were conducted to analyze the microstructure of the coated layer. Results have shown that PEO technique successfully improves wear and corrosion resistance of Al alloy and even better than stainless steel [39].

The polishing process can be integrated with the nitriding process in the same experimental setup by changing the electrolyte and voltage range. The nitriding process and polishing process is the best possible combination of surface improvement technique and successfully achieved by plasma electrolysis technology. Polishing of specimen was carried out after plasma electrolytic nitriding for a very short period of time, such as 2min. The surface roughness of the PEN treated sample was found to be increased, which was compensated by the polishing process by removing loose parts of oxide layers formation takes place on the surface of the specimen [40]. The polishing process can also be studied for plasma electrolytic carbonizing, electrolytic plasma thermo cyclic treatment, and other plasma electrolysis process.

3. Ranges of metals being treated

Ferrous, as well as non-ferrous metals, have been treated by using electrolytic plasma surface treatment. The major focus is given on steel, as it is the backbone material of the manufacturing industry. Different grades of steel have shown positive results for different kinds of surface treatments such as carburizing, nitriding, boronizing, hardening, coating, cleaning, and polishing. Aluminum alloys have also been treated for coating protective surface layers with different materials.

Table1 shows the ranges of metals being treated with electrolytic plasma processes, and all metals shown significant results after the treatment. Aluminum and titanium alloy are generally treated by plasma electrolytic oxidation for coating purposes, and steel was treated by plasma electrolytic hardening. Different types of steel, such as low carbon steel to high-speed tool steel, have developed high wear resistance and corrosion resistance. For corrosion resistance, plasma electrolytic nitriding was used. Both anodic and cathodic processes were conducted, and both processes are shown positive results. In future Chemical Vapour Deposition, can be replaced with Electrolytic Plasma Oxidation due to its fast response and low equipment cost. The coating and polishing industry should focus on the development of the electrolytic plasma process as significant results have been achieved by Electrolytic Plasma Process in this field. Pulse current electrolytic plasma process, and electrolytic plasma hardening processes are mainly used for hardness and wear resistance without the deposition process. In this case, martensite is formed at the surface of the substrate, which causes an increase in hardness and wears resistance. Nickel-based alloy and ductile iron also shown improvement in wear resistance property. In the case of a tool, the steel electrolytic plasma process has proven a novel process for increasing wear resistance and decreasing surface roughness. The friction coefficient has also been studied by using the plasma electrolytic carburizing process. In all types of metals that are treated by the electrolytic plasma process have shown drastically increment for wear resistance, and it is the best-suited process to increase the wear resistance of components. Thus by using the electrolytic plasma process, we can treat types of steel, aluminum alloys, Nickel alloys, Titanium alloys, and ductile iron effectively.

Table data clearly shows that generally, alloy elements were treated by deposition methods such as nitriding, carbonitriding, boriding, and carburizing. The process is suitable for increasing hardness without modification of the chemical composition as well as by changing the chemical structure of the surface of the specimen. Electrolytic plasma hardening introduces martensite and cementite at the surface of the heat treatment, and electrolytic plasma nitriding introduces nitrides at the surface of the specimen.

Table 1. Ranges of metals being treated by PET and industrial scope.

Year	Metal	Type of treatment	Results	Industrial Scope
1997	Medium carbon steel	Pulse current electrolytic plasma heat treatment	Martensite found in hardened steel and the highest heating rate can be achieved by pulse current as compared to D.C. voltage [41]	Toolroom and press tool die
1998	High-speed steel (circular saw)	Electrolytic plasma pulse heating	Service life increases from 1000 to 3000 cuts. Martensite obtained with hardness increased to 62 HRC [42]	Hex saw and cutter
2002	BS Al6082 Aluminium alloy	Plasma electrolytic oxidation	Alumina coating was successfully deposited [39]	Aerospace, automobile and aluminum parts industry
2007	Q235 steel	Plasma electrolysis carbonitriding	When steel treated with 150V for 75s carbonitriding layer of 70-micron forms with hardness 750HV[34]	Machine parts
2008	4340, 4140, 1045, 3215 and 1020 steel	Plasma-electrolysis boronizing	Greater value of hardness and boron layer thickness obtained for 1020 steel[35]	Tool steel
2009	Medium carbon steel (AISI 1040)	Electrolytic plasma thermocyclic treatment	Reliable microstructure and surface hardness were obtained on medium carbon steel [43]	Machine parts

Year	Metal	Type of treatment	Results	Industrial Scope
2010	AISI 4140 steel	Electrolytic plasma thermocyclic treatment	Thickness of hardness layer obtained for different thermo cycles and highest thickness obtained for 300-320V in 42s[3]	Machine parts
2011	AISI 1045 (CK45) carbon steel	Plasma electrolytic nitrocarburizing	Within 8 to 9 min at 200V nitrocarburized layer formed[44]	Tool steel and dies
2012	12Cr18Ni10Ti steel	Electrolytic-plasma cementation (EPC)	Within 7 min carbide layer was formed of thickness 45-65 micron[9]	Punch and die of press tool steel
2014	Q235 low carbon steel	Anodic plasma electrolytic carburizing	Carbon diffused into compound layer successfully, and surface roughness also reduced[45]	Machine parts
2015	St 14 steel	Plasma electrolysis boronizing	Only above 20% borax in electrolyte shows the development of the boride layer on component	Automotive components
2016	T8 carbon steel	Plasma electrolytic carburizing	Steel friction coefficient is reduced from 0.4 to 0.1, and the wear rate also reduced to ¼[47]	Special purpose tools
2017	0.34C-1Cr-1 Ni-1Mo-Fe steel	Electrolyte plasma nitriding	Chromium and nitrides increase hardness as well as wear resistance [29]	Tool steel industry
2018	T8 carbon steel	Cathodic plasma electrolysis	Significantly improved the wear the resistance of carbon steel [27]	Machine parts
2019	Ductile Iron	Electrolytic Plasma Hardening	1050HV hardness achieved with a decrease in wear rate from 4.74×10^{-5} to 0.968×10^{-5} mm^3/m	Piping, the Pump housing industry
2019	Nickel-based K418 superalloy	Cathodic plasma electrolytic deposition	Successfully deposited Si into the surface of the sample for improving layer mechanical properties at high temperature [48].	Coating industry
2019	VT6 Titanium alloy	Plasma Electrolytic Oxidation	After treatment, 80µm thick titanium oxide layer was formed with an increase in wear resistance.	Aerospace Industry and Biomedical industry

4. Future scope in the industry

4.1. Press tool industry.

Electrolytic plasma treatment has shown significant positive results on various types of tool steels. In the press tool industry wear resistance and corrosion resistance, both are necessary, and these properties can be achieved by the electrolytic plasma process. Carbon was successfully transferred on low carbon steel surface by electrolytic plasma carburizing, which results in an increase in hardness up to 700HV, and also anodic process results in reducing surface roughness [45]. The process can be modified for complicated components in which carburizing is needed only on a small portion of the component.

4.2. Biomedical implants.

Titanium alloy is mostly used in biomedical implants, and many researchers have successfully carried out the surface modification of Ti by plasma electrolytic coating and polishing. Surface properties of V22 Titanium alloy have been improved significantly by plasma electrolytic nitriding with 460HV hardness and 20µm hardened layer [23].

4.3. Automobile industry.

Cast iron-based camshaft shown 50-60 HRC after treating with electrolytic plasma hardening [20]. Automotive components like camshafts can be treated with electrolytic plasma processes to induce necessary hardness and wear resistance. Also, performance study may be carried out for conventionally treated components, and PEP treated components. AISI 4140 is the largest and most common material used in tool holders, dies, jigs, and fixtures. Overall mechanical prosperities of this steel have been successfully improved by the electrolytic plasma process [3,43].

4.4. Aerospace industry.

Aluminum, such as BS Al 6082, has also been treated with plasma electrolytic oxidation in which a protective layer of Al2O3 was successfully deposited on the aluminum surface. The wear and corrosion resistance were improved significantly [39]. Aluminum and its alloy are used in large quantities in the aerospace manufacturing industry. The electrolytic plasma process can be considered for the growth of the aerospace industry in terms of quality and production.

5. Summary

Electrolytic Plasma Technology is a novel method for improving surface properties of the low, medium, and high carbon steels. For aluminum alloy also EPT shows positive results for the fabrication coating layer of different materials such as alumina and silicon. Nickel-based Superalloys have also been treated and show improvement in surface properties. The setup required for the process is economical, and no environmental hazardous occurs. The time required to introduce desire properties is in the range of 60s to 5min, which very less as compared to current surface treatments. EPT is a dynamic process, which means hardening, deposition, coating, cleaning, polishing can be done in the same setup with little modification. The coating process can be explored for EPT for different materials where surface properties play an important role. Process parameter optimization, advanced sensors, and data logger system can control the process in a more accurate sense, and better results can be obtained by EPT.

Following conclusions may be drawn from this study:

Electrolytic Plasma hardening and nitriding can be done in the same apparatus within a short time in which hardening is done for hardness improvement, and nitriding is done for corrosion resistance. Electrolytic plasma nitriding and polishing can be done one after another in the same setup.

Surface roughness is affected by the type of electrolytic plasma process. In the cathodic electrolytic plasma process, the surface roughness increases, and in anodic electrolytic plasma process, the surface roughness decreases.

For corrosion resistance, we can increase the corrosion resistance of the metal even greater thans stainless steel.

A coating layer of very small thickness, which is in the range of nanometres, can also be deposited successfully on the surface of metals by the electrolytic plasma process.

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Conflicts of Interest

The authors declare no conflict of interest.

References

1. Gupta, P.; Tenhundfeld, G.; Daigle, E.O.; Ryabkov, D. Electrolytic plasma technology: Science and engineering—An overview. *Surface and Coatings Technology* **2007**, *201*, 8746-8760, https://doi.org/10.1016/j.surfcoat.2006.11.023.
2. Luk, S.F.; Leung, T.P.; Miu, W.S.; Pashby, I. A study of the effect of average preset voltage on hardness during electrolytic surface-hardening in aqueous solution. *Journal of Materials Processing Technology* **1999**, *91*, 245-249,https://doi.org/10.1016/S0924-0136(98)00441-5.
3. Cenk Kumruoğlu, L.; Özel, A. Surface Modification of AISI 4140 Steel Using Electrolytic Plasma Thermocyclic Treatment. *Materials and Manufacturing Processes* **2010**, *25*, 923-931,https://doi.org/10.1080/10426911003720839.
4. Karimi Zarchi, M.; Shariat, M.H.; Dehghan, S.A.; Solhjoo, S. Characterization of nitrocarburized surface layer on AISI 1020 steel by electrolytic plasma processing in an urea electrolyte. *Journal of Materials Research and Technology* **2013**, *2*, 213-220, https://doi.org/10.1016/j.jmrt.2013.02.011.
5. Zagonel, L.F.; Bettini, J.; Basso, R.L.O.; Paredez, P.; Pinto, H.; Lepienski, C.M.; Alvarez, F. Nanosized precipitates in H13 tool steel low temperature plasma nitriding. *Surface and Coatings Technology* **2012**, *207*, 72-78,https://doi.org/10.1016/j.surfcoat.2012.05.081.
6. Skakov, M.; Rakhadilov, B.; Sheffler, M. Influence of Electrolyte Plasma Treatment on Structure, Phase Composition and Microhardness of Steel P6M5. *Key Engineering Materials* **2013**, *531-532*, 627-631,https://doi.org/10.4028/www.scientific.net/KEM.531-532.627.
7. Ayday, A.; Durman, M. Wear properties of aisi 4140 steel modified with electrolytic-plasma technology. *Materiali in Tehnologije***2013**, *47*, 177-180.
8. Liu, R.; Li, X.; Hu, X.; Dong, H. Surface modification of a medical grade Co-Cr-Mo alloy by low-temperature plasma surface alloying with nitrogen and carbon. *Surface and Coatings Technology* **2013**, *232*, 906-911, https://doi.org/10.1016/j.surfcoat.2013.06.122.
9. Kurbanbekov, Sherzod&Skakov, Mazhyn& Scheffler, Michael &Naltaev, Azret. (2012). Changes of Mechanical Properties of Steel 12Cr18Ni10Ti after Electrolytic-Plasma Cementation. Advanced Materials Research.601.59-63. https://doi.org/10.4028/www.scientific.net/AMR.601.59.
10. Liang, J. A study on the cleaning and modification of metal surfaces by direct current cathodic electrolytic plasma process LSU Doctoral Dissertations. 2013; pp. 618.
11. Skonieski, A.F.O.; Santos, G.R.d.; Hirsch, T.K.; Rocha, A.d.S. Metallurgical response of an AISI 4140 steel to different plasma nitriding gas mixtures. *Materials Research* **2013**, *16*, 884-890,https://doi.org/10.1590/S1516-14392013005000073.
12. Duradji, V.N.; Kaputkin, D.; Duradji, A. Aluminum Treatment in the Electrolytic Plasma During the Anodic Process. *Journal of Engineering Science and Technology Review* **2017**, *10*, 81-84,https://doi.org/10.25103/jestr.103.11.
13. Duradji, V.; Kaputkin, D. Metal Surface Treatment in Electrolyte Plasma during Anodic Process. *Journal of The Electrochemical Society* **2016**, *163*, E43-E48, https://doi.org/10.1149/2.0011603jes.
14. Dewan, M.W.; Liang, J.; Wahab, M.A.; Okeil, A.M. Effect of post-weld heat treatment and electrolytic plasma processing on tungsten inert gas welded AISI 4140 alloy steel. *Materials & Design (1980-2015)* **2014**, *54*, 6-13, https://doi.org/10.1016/j.matdes.2013.08.035.
15. Kashapov, L.N.; Kashapov, N.F.; Kashapov, R.N.; Semushin, V.D. Changes of thermal balance in a plasma-electrolyte system according to the shape of the applied voltage. *Journal of Physics: Conference Series* **2016**, *669*,https://doi.org/10.1088/1742-6596/669/1/012028.
16. Ozel, A.; Kumruoglu, L.C. Wear Performance of Hardened 1.2333 Cold work Tool Steel by Plasma Electrolysis. *Acta physica Polonica A***2014**, *125*,https://doi.org/10.12693/APhysPolA.125.304.
17. cheuer, C.J.; Cardoso, R.P.; Brunatto, S.F. Low-temperature Plasma Assisted Thermochemical Treatments of AISI 420 Steel: Comparative Study of Obtained Layers. *Materials Research* **2015**, *18*, 1392-1399,https://doi.org/10.1590/1516-1439.013815.
18. Rakhadilov, B.; Zhurerova, L.; Pavlov, A. Method of Electrolyte-Plasma Surface Hardening of 65G and 20GL Low-Alloy Steels Samples. *IOP Conference Series: Materials Science and Engineering* **2016**, *142*, https://doi.org/10.1088/1757-899X/142/1/012028.
19. Belkin, P.N.; Kusmanov, S.A. Plasma electrolytic hardening of steels: Review. *Surface Engineering and Applied Electrochemistry* **2016**, *52*, 531-546, https://doi.org/10.3103/S106837551606003X.
20. Dayanç, A.; Karaca, B.; Kumruoğlu, L. The Cathodic Electrolytic Plasma Hardening of Steel and Cast Iron Based Automotive Camshafts. *Acta Physica Polonica A***2017,***131*, 374-379,https://doi.org/10.12693/APhysPolA.131.374.
21. Ozbek, Y. Effect of Heat Treatment and Pulse Plasma Process on Surface Properties of Steels. *Acta Physica Polonica A*. **2017**, *131*, 182-185, https://doi.org/10.12693/APhysPolA.131.182.

22. Kusmanov, S.A.; Dyakov, I.G.; Kusmanova, Y.V.; Belkin, P.N. Surface Modification of Low-Carbon Steels by Plasma Electrolytic Nitrocarburising. *Plasma Chemistry and Plasma Processing* **2016**, *36*, 1271-1286, https://doi.org/10.1007/s11090-016-9724-3.
23. Smirnov, A.A.; Kusmanov, S.A.; Kusmanova, I.A.; Belkin, P.N. Effect of electrolyte depletion on the characteristics of the anodic plasma electrolytic nitriding of a VT22 titanium alloy. *Surface Engineering and Applied Electrochemistry* **2017**, *53*, 413-418,https://doi.org/10.3103/S106837551705012X.
24. Belkin, P.N.; Kusmanov, S.A. Plasma electrolytic nitriding of steels. *Journal of Surface Investigation: X-ray, Synchrotron and Neutron Techniques* **2017**, *11*, 767-789,https://doi.org/10.1134/S1027451017020045.
25. Hussein, R.O.; Nie, X.; Northwood, D.O.; Yerokhin, A.; Matthews, A. Spectroscopic study of electrolytic plasma and discharging behaviour during the plasma electrolytic oxidation (PEO) process. *Journal of Physics D: Applied Physics* **2010**, *43*.
26. Belkin, P.N.; Kusmanov, S.A.; Dyakov, I.G.; Silkin, S.A.; Smirnov, A.A. Increasing Wear Resistance of Titanium Alloys by Anode Plasma Electrolytic Saturation with Interstitial Elements. *Journal of Materials Engineering and Performance* **2017**, *26*, 2404-2410,https://doi.org/10.1007/s11665-017-2655-1.
27. Wu, J.; Dong, L.; Deng, J.; Hou, D.; Li, G.; Li, D.; Xue, W. Direct growth of oxide layer on carbon steel by cathodic plasma electrolysis. *Surface and Coatings Technology* **2018**, *338*, 63-68, https://doi.org/10.1016/j.surfcoat.2018.01.080.
28. Noori, S.M.; Dehghanian, C. Characterization of nitrocarburized coating by plasma electrolytic saturation. *Acta MetallurgicaSlovaca***2018**, *24*,https://doi.org/10.12776/ams.v24i1.957.
29. Popova, N.; Erygina, L.; Nikonenko, E.; Skakov, M. Phase composition of perlite steel modified by electrolyte plasma nitriding. *AIP Conference Proceedings* **2017**, *1899*,https://doi.org/10.1063/1.5009847.
30. Kusmanov, S.A.; Tambovskiy, I.V.; Naumov, A.R.; Dyakov, I.G.; Belkin, P.N. Anode plasma electrolytic boronitrocarburising of low-carbon steel. *Surface Engineering and Applied Electrochemistry* **2015**, *51*, 462-467,https://doi.org/10.3103/S1068375515050099.
31. Çavuşlu, F.; Usta, M. Kinetics and mechanical study of plasma electrolytic carburizing for pure iron. *Applied Surface Science* **2011**, *257*, 4014-4020, https://doi.org/10.1016/j.apsusc.2010.11.167.
32. Belkin, P.N.; Naumov, A.; Shadrin, S.; Dyakov, I.G.; Zhirov, A.; Kusmanov, S.A.; Mukhacheva, T. Anodic Plasma Electrolytic Saturation of Steels by Carbon and Nitrogen. *Advanced Materials Research* **2013**, *704*, 37-42,https://doi.org/10.4028/www.scientific.net/AMR.704.37.
33. Ayday, A.; Durman, M. Wear performance of ductile iron after electrolytic plasma hardening. *Metallic Materials* **2019**, *57*, 19-26,https://doi.org/10.4149/km_2019_1_19.
34. Shen, D.J.; Wang, Y.L.; Nash, P.; Xing, G.Z. A novel method of surface modification for steel by plasma electrolysis carbonitriding. *Materials Science and Engineering: A* **2007**, *458*, 240-243, https://doi.org/10.1016/j.msea.2006.12.067.
35. Béjar, M.A.; Henríquez, R. Surface hardening of steel by plasma-electrolysis boronizing. *Materials & Design* **2009**, *30*, 1726-1728, https://doi.org/10.1016/j.matdes.2008.07.006.
36. Dyakov, I.G.; Burov, S.V.; Belkin, P.N.; Rozanov, E.V.; Zhukov, S.A. Increasing wear and corrosion resistance of tool steel by anodic plasma electrolytic nitriding. *Surface and Coatings Technology* **2019**, *362*, 124-131, https://doi.org/10.1016/j.surfcoat.2019.01.107.
37. Roy, A.; Tewari, R.K.; Sharma, R.C.; Shekhar, R. Feasibility study of aqueous electrolyte plasma nitriding. *Surface Engineering* **2007**, *23*, 243-246,https://doi.org/10.1179/174329407X215285.
38. Yerokhin, A.L.; Nie, X.; Leyland, A.; Matthews, A. Characterisation of oxide films produced by plasma electrolytic oxidation of a Ti–6Al–4V alloy. *Surface and Coatings Technology* **2000**, *130*, 195-206, https://doi.org/10.1016/S0257-8972(00)00719-2.
39. Nie, X.; Meletis, E.I.; Jiang, J.C.; Leyland, A.; Yerokhin, A.L.; Matthews, A. Abrasive wear/corrosion properties and TEM analysis of Al2O3 coatings fabricated using plasma electrolysis. *Surface and Coatings Technology* **2002**, *149*, 245-251,https://doi.org/10.1016/S0257-8972(01)01453-0.
40. Kusmanov, S.; Zhirov, A.; Kusmanova, I.; Belkin, P. Aspects of anodic plasma electrolytic polishing of nitrided steel. *Surface Engineering* **2019**, *35*, 507-511, https://doi.org/10.1080/02670844.2017.1406574.
41. Luk, S.F.; Leung, T.P.; Miu, W.S.; Pashby, I. Heating performance of electrolytic heat-treatment in aqueous solution by pulse current. *Journal of Materials Processing Technology* **1997**, *63*, 833-838, https://doi.org/10.1016/S0924-0136(96)02734-3.
42. Tyulyapin, A.N.; Tyurin, Y.N.; Traino, A.I.; Yusupov, V.S. Electrolyte-plasma hardening of circular saws. *Metal Science and Heat Treatment* **1998**,*40*, 11-13,https://doi.org/10.1007/BF02468498.
43. Kumruoglu, L.C.; Becerik, D.A.; Ozel, A.; Mimaroglu, A. Surface Modification of Medium Carbon Steel by Using Electrolytic Plasma Thermocyclic Treatment. *Materials and Manufacturing Processes* **2009**, *24*, 781-785, https://doi.org/10.1080/10426910902813034.
44. Rastkar, A.R.; Shokri, B. Surface modification and wear test of carbon steel by plasma electrolytic nitrocarburizing. *Surface and Interface Analysis* **2012**, *44*, 342-351,https://doi.org/10.1002/sia.3808.
45. Kusmanov, S.A.; Shadrin, S.Y.; Belkin, P.N. Carbon transfer from aqueous electrolytes to steel by anode plasma electrolytic carburising. *Surface and Coatings Technology* **2014**, *258*, 727-733, https://doi.org/10.1016/j.surfcoat.2014.08.005.
46. Tavakoli, H.; Mousavi Khoie, S.M.; Rasooli, F.; Marashi, S.P.H.; Momeni, F. Electrochemical and physical

characteristics of the steel treated by plasma-electrolysis boronizing. *Surface and Coatings Technology* **2015**, *276*, 529-533,https://doi.org/10.1016/j.surfcoat.2015.06.020.
47. Wu, J.; Wang, B.; Zhang, Y.; Liu, R.; Xia, Y.; Li, G.; Xue, W. Enhanced wear and corrosion resistance of plasma electrolytic carburized layer on T8 carbon steel. *Materials Chemistry and Physics* **2016**, *171*, 50-56, https://doi.org/10.1016/j.matchemphys.2015.09.047.
48. Xue, J.; Wang, D.; Li, M.; Jia, R. Preparation of silicon-modified gamma alumina coating through cathodic plasma electrolytic deposition. *Ceramics International* **2019**, *45*, 19345-19350, https://doi.org/10.1016/j.ceramint.2019.06.186.
49. Kusmanov, S.A.; Smirnov, A.A.; Kusmanova, Y.V.; Belkin, P.N. Anode plasma electrolytic nitrohardening of medium carbon steel. *Surface and Coatings Technology* **2015**, *269*, 308-313, https://doi.org/10.1016/j.surfcoat.2014.12.033.
50. Kusmanov, S.A.; Kusmanova, Y.V.; Naumov, A.R.; Belkin, P.N. Features of anode plasma electrolytic nitrocarburising of low carbon steel. *Surface and Coatings Technology* **2015**, *272*, 149-157, https://doi.org/10.1016/j.surfcoat.2015.04.011.
51. Belkin, P.N.; Kusmanov, S.A.; Smirnov, A.A. Plasma Electrolytic Hardening and Nitrohardening of Medium Carbon Steels. *Materials Science Forum* **2016**, *844*, 146-152,https://doi.org/10.4028/www.scientific.net/msf.844.146.
52. Ablyaz, T.; Muratov, K.; Ushomirskaya, L.; Zarubin, D.; Sidhu, S. Electrolytic plasma polishing technique for improved surface finish of ED machined components. *Engineering Solid Mechanics* **2019**, *7*, 131-136, https://doi.org/10.5267/j.esm.2019.3.003.
53. Rakoch, A.G.; Van Truong, P.; Gladkova, A.A.; Predein, N.A. Phase Composition and Wear Resistance of Coatings Formed on the VT6 Titanium Alloy by Plasma Electrolytic Oxidation. *Russian Journal of Non-Ferrous Metals* **2019**, *60*, 200-206, https://doi.org/10.3103/S106782121902010X.
54. Yongfu Zhang, Aiming Bu, Yan Xiang, Yunjie Yang, Weiwei Chen, Huanwu Cheng, Lu Wang,Improving corrosion resistance of carbonyl iron powders by plasma electrolytic deposition, Materials & Design, Volume 188,2020,108480,ISSN 0264-1275, https://doi.org/10.1016/j.matdes.2020.108480.
55. Tabieva, E.E.; Zhurerova, L.G.; Baizhan, D. Influence of Electrolyte-Plasma Hardening Technological Parameters on the Structure and Properties of Banding Steel 2. *Key Engineering Materials* **2020**, *839*, 57-62, https://doi.org/10.4028/www.scientific.net/kem.839.57.
56. Popova, N.A.; Potekaev, A.I.; Nikonenko, E.L.; Klopotov, A.A.; Bayatanova, L.B.; Nikonenko, A.V.; Kislitsin, S.B. Phase Composition and Thin Structure of Steel Surface after Plasma Electrolytic Carbonitriding. *Russian Physics Journal* **2020**, *62*, 1794-1800, https://doi.org/10.1007/s11182-020-01908-9.
57. Satbayeva, Z.A.; Zhurerova, L.G.; Tabieva, E.E. Plasma Electrolytic Cementation of 0.3C-1Cr-1Mn-1Si-Fe Steel. *Key Engineering Materials* **2020**, *839*, 196-202,https://doi.org/10.4028/www.scientific.net/kem.839.196.
58. Kellogg, H.H. Anode Effect in Aqueous Electrolysis. *Journal of The Electrochemical Society* **1950**, *97*, 133,https://doi.org/10.1149/1.2777980.
59. Hickling, A. Modern Aspects of Electrochemistry. Volume 6, Butterworths, Springer Science & Business Media.
60. Yerokhin, A.L.; Nie, X.; Leyland, A.; Matthews, A.; Dowey, S.J. Plasma electrolysis for surface engineering. *Surface and Coatings Technology* **1999**, *122*, 73-93, https://doi.org/10.1016/S0257-8972(99)00441-7.
61. Hussein, R.O.; Zhang, P.; Nie, X.; Xia, Y.; Northwood, D.O. The effect of current mode and discharge type on the corrosion resistance of plasma electrolytic oxidation (PEO) coated magnesium alloy AJ62. *Surface and Coatings Technology* **2011**, *206*, 1990-1997, https://doi.org/10.1016/j.surfcoat.2011.08.060.
62. Sengupta, S.K.; Singh, O.P. Contact glow discharge electrolysis: a study of its onset and location. *Journal of Electroanalytical Chemistry and Interfacial Electrochemistry* **1991**, *301*, 189-197, https://doi.org/10.1016/0022-0728(91)85469-6.
63. Cionea, C. *Microstructural Evolution Of Surface Layers During Electrolytic Plasma Processing*. 2010.
64. Arrabal, R.; Matykina, E.; Viejo, F.; Skeldon, P.; Thompson, G.E. Corrosion resistance of WE43 and AZ91D magnesium alloys with phosphate PEO coatings. *Corrosion Science* **2008**, *50*, 1744-1752,https://doi.org/10.1016/j.corsci.2008.03.002.
65. Mashtalyar, D.V.; Gnedenkov, S.V.; Sinebryukhov, S.L.; Imshinetskiy, I.M.; Gnedenkov, A.S.; Bouznik, V.M. Composite coatings formed using plasma electrolytic oxidation and fluoroparaffin materials. *Journal of Alloys and Compounds* **2018**, *767*, 353-360,https://doi.org/10.1016/j.jallcom.2018.07.085.
66. Yerokhin, A.L.; Nie, X.; Leyland, A.; Matthews, A.; Dowey, S.J. Plasma electrolysis for surface engineering. *Surface and Coatings Technology* **1999**, *122*, 73-93, https://doi.org/10.1016/S0257-8972(99)00441-7.
67. Sengupta, S.K.; Singh, O.P. Contact glow discharge electrolysis: a study of its chemical yields in aqueous inert-type electrolytes. *Journal of Electroanalytical Chemistry* **1994**, *369*, 113-120,https://doi.org/10.1016/0022-0728(94)87089-6.
68. Rudnev, V.S.; Yarovaya, T.P.; Nedozorov, P.M.; Mansurov, Y.N. Wear-resistant oxide coatings on aluminum alloy formed in borate and silicate aqueous electrolytes by plasma electrolytic oxidation. *Protection of Metals and Physical Chemistry of Surfaces* **2017**, *53*, 466-474,https://doi.org/10.1134/S2070205117030200.
69. Timoshenko, A.V.; Magurova, Y.V. Investigation of plasma electrolytic oxidation processes of magnesium alloy MA2-1 under pulse polarisation modes. *Surface and Coatings Technology* **2005**, *199*, 135-140,

https://doi.org/10.1016/j.surfcoat.2004.09.036.
70. Lou, B.S.; Lee, J.W.; Tseng, C.M.; Lin, Y.Y.; Yen, C.A. Mechanical property and corrosion resistance evaluation of AZ31 magnesium alloys by plasma electrolytic oxidation treatment: Effect of MoS2 particle addition. *Surface and Coatings Technology* **2018**, *350*, 813-822, https://doi.org/10.1016/j.surfcoat.2018.04.044.
71. Gnedenkov, S.V.; Sinebryukhov, S.L.; Tkachenko, I.A.; Mashtalyar, D.V.; Ustinov, A.Y.; Samokhin, A.V.; Tsvetkov, Y.V. Magnetic properties of surface layers formed on titanium by plasma electrolytic oxidation. *Inorganic Materials: Applied Research* **2012**, *3*, 151-156,https://doi.org/10.1134/S2075113312020062.
72. White, L.; Koo, Y.; Yun, Y.; Sankar, J. TiO_2Deposition on AZ31 Magnesium Alloy Using Plasma Electrolytic Oxidation. *Journal of Nanomaterials* **2013**, *2013*https://doi.org/10.1155/2013/319437.
73. Pogrebnyak, A.D.; Kaverina, A.S.; Kylyshkanov, M.K. Electrolytic plasma processing for plating coatings and treating metals and alloys. *Protection of Metals and Physical Chemistry of Surfaces* **2014**, *50*, 72-87, https://doi.org/10.1134/S2070205114010092.
74. Shadrin, S.Y.; Belkin, P.N. Analysis of models for calculation of temperature of anode plasma electrolytic heating. *International Journal of Heat and Mass Transfer* **2012**, *55*, 179-186, https://doi.org/10.1016/j.ijheatmasstransfer.2011.09.001.
75. Ren, J.; Yao, M.; Yang, W.; Li, Y.; Gao, J. Recent progress in the application of glow-discharge electrolysis plasma. *Central European Journal of Chemistry* **2014**, *12*, 1213-1221, https://doi.org/10.2478/s11532-014-0575-6.
76. Sengupta, S.K.; Srivastava, A.K.; Singh, R. Contact glow discharge electrolysis: a study on its origin in the light of the theory of hydrodynamic instabilities in local solvent vaporisation by Joule heating during electrolysis. *Journal of Electroanalytical Chemistry* **1997**, *427*, 23-27,https://doi.org/10.1016/S0022-0728(96)05044-9.
77. D'yakov, I.G.; Belkin, V.S.; Shadrin, S.Y.; Belkin, P.N. Peculiarities of heat transfer at anodic plasma electrolytic treatment of cylindrical pieces. *Surface Engineering and Applied Electrochemistry* **2014**, *50*, 346-355, https://doi.org/10.3103/S1068375514040061.
78. Belkin, P.N.; Pasinkovskii, E.A. Heat treatment and case hardening of steels subjected to heat in electrolyte solutions. *Metal Science and Heat Treatment* **1989**, *31*, 331-337,https://doi.org/10.1007/BF00801655.
79. Pogrebnyak, A.D.; Tyurin, Y.N. Modification of material properties and coating deposition using plasma jets. *Physics-Uspekhi***2005**, *48*, 487-514,https://doi.org/10.1070/PU2005v048n05ABEH002055.
80. Klapkiv, M.D. State of an electrolytic plasma in the process of synthesis of oxides based on aluminum. *Materials Science* **1996**, *31*, 494-499,https://doi.org/10.1007/BF00559144.
81. BaratiDarband, G.; Aliofkhazraei, M.; Hamghalam, P.; Valizade, N. Plasma electrolytic oxidation of magnesium and its alloys: Mechanism, properties and applications. *Journal of Magnesium and Alloys* **2017**, *5*, 74-132,https://doi.org/10.1016/j.jma.2017.02.004.
82. Pogrebnjak, A.D.; Kul'ment'eva, O.P.; Kobzev, A.P.; Tyurin, Y.N.; Golovenko, S.I.; Boiko, A.G. Mass transfer and doping during electrolyte-plasma treatment of cast iron. *Technical Physics Letters* **2003**, *29*, 312-315, https://doi.org/10.1134/1.1573301.
83. Electrolytic Plasma Processing for Sequential Cleaning and Coating Deposition for Cadmium Plating Replacement, Project WP-1406 Annual Report to U.S. Department of Defense Strategic Environmental Research and Development Program, December 2005.
84. Luk, S.F.; Leung, T.P.; Miu, W.S.; Pashby, I. Development of electrolytic heat-treatment in aqueous solution. *Journal of Materials Processing Technology* **1998**, *84*, 189-192, https://doi.org/10.1016/S0924-0136(98)00086-7.
85. Bayati, M.R.; Molaei, R.; Janghorban, K. Surface Modification of AISI 1045 Carbon Steel by the Electrolytic Plasma Process. *Metallurgical and Materials Transactions A* **2010**, *41*, 906-911,https://doi.org/10.1007/s11661-009-0165-y.
86. Belkin, P.N.; Kusmanov, S.A. Plasma Electrolytic Boriding of Steels and Titanium Alloys. *Surface Engineering and Applied Electrochemistry* **2019**, *55*, 1-30, https://doi.org/10.3103/S106837551901006X.
87. Makishi, T.; Nakata, K. Surface hardening of nickel alloys by means of plasma nitriding. *Metallurgical and Materials Transactions A* **2004**, *35*, 227-238,https://doi.org/10.1007/s11661-004-0123-7.
88. Stavrev, D.S.; Kaputkina, L.M.; Kirov, S.K.; Shamonin, Y.V.; Prokoshkina, V.G. Effect of plasma-arc treatment on structural transformations and surface hardening of carbon and alloyed steels. *Metal Science and Heat Treatment* **1996**, *38*, 382-385, https://doi.org/10.1007/BF01395643.
89. Aliofkhazraei, M.; Rouhaghdam, A.S.; Roohzendeh, M. Study of bipolar pulsed plasma electrolytic carbonitriding on nanostructure of compound layer for a gamma Ti-Al alloy. *Frontiers of Materials Science in China* **2008**, *2*, 48-54,https://doi.org/10.1007/s11706-008-0009-5.
90. Aliofkhazraei, M.; Rouhaghdam, A.S. Study of bipolar pulsed nanocrystalline plasma electrolytic carbonitriding on nanostructure of compound layer. *Russian Journal of Non-Ferrous Metals* **2008**, *49*, 212-218,https://doi.org/10.3103/S1067821208030152.
91. Belkin, P.N.; Borisov, A.M.; Kusmanov, S.A. Plasma electrolytic saturation of titanium and its alloys with light elements. *Journal of Surface Investigation. X-ray, Synchrotron and Neutron Techniques* **2016**, *10*, 516-535, https://doi.org/10.1134/S1027451016030058.
92. Kolomeichenko, A.V.; Kravchenko, I.N. Elemental Composition and Microhardness of the Coatings Prepared on Faced Aluminum Alloys by Plasma Electrolytic Oxidation in a Silicate–Alkaline Electrolyte. *Russian*

Metallurgy (Metally) **2019**, *2019*, 1410-1413, https://doi.org/10.1134/S0036029519130147.
93. Kuznetsov, Y.A.; Kravchenko, I.N.; Goncharenko, V.V.; Glinskii, M.A. Machining of the Ceramic Oxide Coating Formed by Plasma Electrolytic Oxidation. *Russian Metallurgy (Metally)* **2018**, *2018*, 1268-1272, https://doi.org/10.1134/S003602951813013X.
94. Kovalenko, V.S., Verkhoturov, A.D., Golovko, L.F. *et al.* Laser surface hardening and electric-spark surface hardening of materials. *J Russ Laser Res* **9,** 1–175 (1988). https://doi.org/10.1007/BF01120344 .
95. Aver'yanov, E.E.; Galimzyanov, R.M.; Gilyazova, K.Z.; Popov, V.A.; Rabinovich, A.V.; Shagiakhmetov, R.A. Use of plasma-electrolytic anodizing to produce thick-layer coatings on aluminum alloys. *Chemical and Petroleum Engineering* **1991**, *27*, 230-232,https://doi.org/10.1007/BF01150229.
96. Imbirovich, N.Y.; Klapkiv, M.D.; Posuvailo, V.M.; Povstyanoi, O.Y. Properties of Ceramic Oxide Coatings on Magnesium and Titanium Alloys Synthesized in Electrolytic Plasma. *Powder Metallurgy and Metal Ceramics* **2015**, *54*, 47-52, https://doi.org/10.1007/s11106-015-9678-7.
97. Zhirov, A.V.; Belkin, P.N.; Shadrin, S.Y. Heat Transfer in the Anode Region in Plasma-Electrolytic Heating of a Cylindrical Sample. *Journal of Engineering Physics and Thermophysics***2017**, *90*, 862-872, https://doi.org/10.1007/s10891-017-1635-5.
98. Kusmanov, S.A.; Tambovskii, I.V.; Naumov, A.R.; D’yakov, I.G.; Kusmanova, I.A.; Belkin, P.N. Anodic electrolytic-plasma borocarburizing of low-carbon steel. *Protection of Metals and Physical Chemistry of Surfaces* **2017**, *53*, 488-494, https://doi.org/10.1134/S2070205117030121.
99. Shadrin, S.Y.; Belkin, P.N.; Tambovskiy, I.V.; Kusmanov, S.A. Physical Features of Anodic Plasma Electrolytic Carburising of Low-Carbon Steels. *Plasma Chemistry and Plasma Processing* **2020**, *40*, 549-570, https://doi.org/10.1007/s11090-020-10062-6.
100. Liang, J.; Wahab, M.A.; Guo, S.M. Corrosion Behavior of SS 304 with Ball Milling and Electrolytic Plasma Treatment in NaCl Solution. In Proceedings of Mechanics of Time-Dependent Materials and Processes in Conventional and Multifunctional Materials, Volume 3, New York, NY, 2011; pp. 73-80,https://doi.org/10.1007/978-1-4614-0213-8_11.
101. Klapkiv, M.D.; Chuchmarev, O.S.; Sydor, P.Y.; Posuvailo, V.M. Thermodynamics of the interaction of aluminum, magnesium, and zirconium with components of an electrolytic plasma. *Materials Science* **2000**, *36*, 66-79, https://doi.org/10.1007/BF02805119.
102. Rudnev, V.S.; Yarovaya, T.P.; Kilin, K.N.; Malyshev, I.V. Plasma-electrolytic oxidation of valve metals in Zr(IV)-containing electrolytes. *Protection of Metals and Physical Chemistry of Surfaces* **2010**, *46*, 456-462, https://doi.org/10.1134/S2070205110040118.
103. Kumari, R.; Blawert, C.; Majumdar, J.D. Microstructures and Properties of Plasma Electrolytic Oxidized Ti Alloy (Ti-6Al-4V) for Bio-implant Application. *Metallurgical and Materials Transactions A* **2016**, *47*, 788-800, https://doi.org/10.1007/s11661-015-3256-y.
104. Aliofkhazraei, M.; Taheri, P.; SabourRouhaghdam, A.; Dehghanian, C. Study of nanocrystalline plasma electrolytic carbonitriding for CP-Ti. *Materials Science* **2007**, *43*, 791-799,https://doi.org/10.1007/s11003-008-9024-z.