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A review on the surface treatments used to create wear and corrosion resistant steel surfaces

Aşınma ve korozyona dirençli çelik yüzeyler oluşturmak ıçin kullanılan yüzey işlemleri üzerine bir derleme

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A Review on the Surface Treatments Used to Create Wear and Corrosion Resistant Steel Surfaces

Highlights

- *Review on the coating techniques on steel*
- *Review on the methods used to improve the wear resistance of steel*
- *Review on the methods used to improve the corrosion resistance of steel*

Graphical Abstract

Steel is one of the most important engineering materials that can be used for various industries such as aerospace, the arms industry, automotive, etc. due to its' superior properties. However, its low corrosion and wear resistance properties limit its' usage area and lifespan. By improving the corrosion and wear resistance of steels with appropriate surface treatments, material losses caused by corrosion and wear and the problems related to these losses can be reduced or prevented.

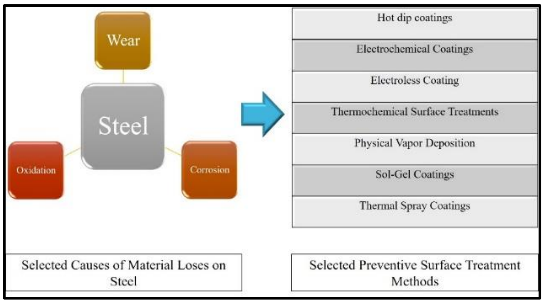

Figure. Graphical abstract of this study.

Aim

The main goal of this study is to review the coating methods and surface treatments used to improve the corrosion and wear resistance of steel The performance of coatings and surface treatments used to increase steel's corrosion and wear resistance is influenced by the working environment, temperature, and the effects of wear and corrosion on steel. Therefore, knowledge is required in the selection of appropriate methods applied to reduce or prevent material losses due to wear and corrosion. In this study, coating and surface treatments applied to steels are explained and their effects on wear and corrosion resistance are evaluated.

Design & Methodology

The coating and surface treatments used to improve the wear and corrosion resistance of steels were investigated. Information about the selected coating and surface treatments are given and their effects on the corrosion and wear resistance of steels are stated.

Originality

The performance changes of the preventive processes due to variables such as temperature and time are stated. Performance-enhancing post-processes are mentioned.

Findings

Coating and other surface treatments improve the wear and corrosion resistance of steel.

Conclusion

There are many limiting factors in the selection of preventive treatments applied to improve the wear and corrosion properties of steel materials. In addition, the properties of preventive treatments applied to steels also change with the effect of variables such as time and temperature. Therefore, the evaluation of the process parameters and the working environment of the steels have critical importance in the selection of suitable processes. It is also possible to increase the performance of preventive processes by post-treatments such as heat treatment.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

A Review on the Surface Treatments Used to Create Wear and Corrosion Resistant Steel Surfaces

Derleme Makalesi / Review Article

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ABSTRACT

Steel alloys are one of the most used engineering material classes due to their superior properties such as yield and tensile strength, good thermal conductivity, machinability, formability, ductility, magnetic properties, and recyclability. In addition to its advantages, steel suffers from two main factors that limit its use, namely wear and corrosion. Wear and corrosion, separately or in combination, cause a material loss in steel, resulting in increased costs in industrial production. However, with appropriate surface treatments, wear and corrosion of steels can be prevented or kept to a minimum. Corrosion and wear resistances provided by appropriate methods have the potential to reduce costs and also expand the set of suitable materials that designers can choose from. In this study, brief information about steel is given and then preventive applications against wear and corrosion of steel materials are examined. Definitions were made about surface treatments such as hot-dip coatings, electrochemical coatings, electroless coatings, thermochemical surface treatments, sol-gel coatings, chemical vapor deposition (CVD), thermal spray coatings, physical vapor deposition (PVD), and the effects of surface treatments on the wear and corrosion properties of steels were investigated. In addition, the effects of some process parameters of surface treatments and post-treatments such as heat treatment on corrosion and wear behavior are presented.

Keywords: Corrosion, steel, surface treatments, wear.

Aşınma ve Korozyona Dirençli Çelik Yüzeyler Oluşturmak Için Kullanılan Yüzey İşlemleri Üzerine Bir Derleme

ÖZ

Çelik alaşımları, akma ve çekme mukavemeti, iyi ısıl iletkenlik, işlenebilirlik, şekillendirilebilirlik, süneklik, manyetik özellikler ve geri dönüştürülebilirlik gibi üstün özelliklerinden dolayı en çok kullanılan mühendislik malzemesi sınıflarından biridir. Avantajlarına ek olarak, çelik, kullanımını sınırlayan iki ana faktörden muzdariptir: aşınma ve korozyon. Aşınma ve korozyon, ayrı ayrı veya bir arada, çeliklerde malzeme kaybına neden olarak endüstriyel üretimde maliyetlerin artmasına neden olur. Ancak uygun yüzey işlemleri ile çeliklerin aşınması ve korozyonu önlenebilir veya minimumda tutulabilir. Uygun yöntemlerle sağlanan korozyon ve aşınma direnci, maliyetleri düşürme potansiyeline sahiptir ve endüstriyel tasarımcılara geniş bir malzeme seçimi yelpazesi sunar. Bu çalışmada çelikler hakkında kısaca bilgi verilmiş ardından çelik malzemelerin aşınma ve korozyona karşı önleyici uygulamaları incelenmiştir. Sıcak daldırma kaplamalar, elektrokimyasal kaplamalar, akımsız kaplamalar, termokimyasal yüzey işlemleri, sol-jel, termal sprey kaplamalar, fiziksel buhar biriktirme, kimyasal buhar biriktirme, gibi yüzey işlemleri ile yüzey işlemlerinin çeliklerin aşınma ve korozyon direnci üzerindeki etkileri hakkında tanımlamalar yapılmıştır. Ayrıca proses parametrelerinin ve yüzey işleminden sonra uygulanan ısıl işlem gibi ardıl işlemlerin çeliklerin korozyon ve aşınma davranışı üzerindeki etkileri sunulmaktadır.

Anahtar Kelimeler: Aşınma, çelik, korozyon, yüzey işlemleri.

1. INTRODUCTION

Steel is an iron-carbon alloy, which is one of the main elements of industrial production, depending on its mechanical and physical properties. Steels are a popular material in almost every industry because their properties can be improved by alloying during production and by heat and mechanical post-treatment processes. Moreover, steel is named the world's most recycled material and its recyclability rate is 100% [1]. Thanks to the fact that these materials can be designed, hardened, and processed in different ways, steel is a preferable material in weapon production in the defense industry. Its usage areas in the year 2020 are shown in Figure 1.

Steel is a highly sought-after material, but it suffers from two issues: wear and corrosion, which cause material loss depending on working conditions and time. Material loss due to wear and corrosion causes economic damage of billions of dollars, but it is possible to minimize this damage with appropriate surface treatments. Many

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methods have been developed to prevent material loss due to wear and corrosion in steel, so the need to classify these methods has arisen. Anti-corrosion and anti-wear surface treatments are generally applied by changing the surface chemistry and surface metallurgy of steel materials or by creating a new layer on the surface [3].

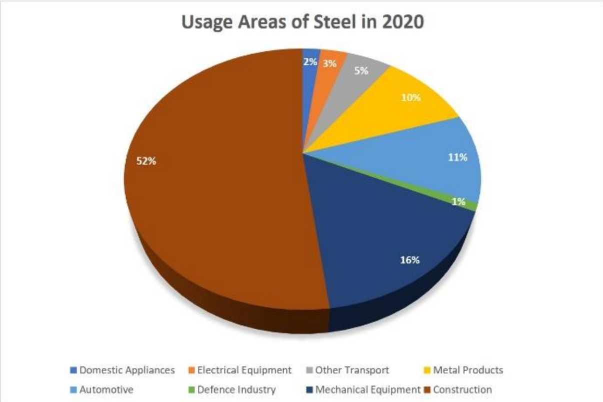

Figure 1. Usage areas of Steel in 2020 from the world steel association (2020) [2].

This study aims to briefly introduce selected anti-corrosion and anti-wear surface treatments, to reveal the properties of surface treatments and the effects of surface treatments on the wear and corrosion resistance of steels.

2. PREVENTIVE SURFACE TREATMENTS AGAINST WEAR AND CORROSION

Surface treatments are critical to eliminating or minimizing material losses due to wear and corrosion in steel. In addition, different properties of steel such as oxidation resistance, mechanical and electrical-electronic properties, and thermal properties can be improved by surface treatments [4]. Anti-corrosion and anti-wear surface treatments applied to steel materials are listed in Figure 2.

Steels can be treated with a variety of surface treatments, as shown in Figure 2. The type of substrate steel material, the geometry of the substrate, and the operating conditions of the substrate should all be considered when deciding on the surface treatment to be used to prevent steel wear and corrosion. Simultaneously, knowledge of surface treatment properties is required to achieve the proper match. As a result, selected surface treatments were investigated at this stage of the study.

2.1. HOT-DIP COATINGS

Hot-dip coatings are surface treatments that are generally applied to increase corrosion resistance and are preferred due to their low cost. The coating layer obtained by this method acts as a barrier or sacrificial anode, protecting the substrate material against corrosion. The chemical composition of the substrate and process variables such as bath composition, temperature, and immersion time affect the corrosion performance of hot-dip coatings [6]. Therefore, with the optimization of these variables, it is possible to create baths where desired performances can be achieved. Zinc is generally preferred in hot-dip coating method applications [7]. The hot-dipping method consists of three successive stages. The first of these stages is the cleaning process, which is of great importance in almost every surface treatment. The main step of the process is the dipping process, where the coating takes place. In the third stage, there are post-treatments in which the coating performance can be increased [8].

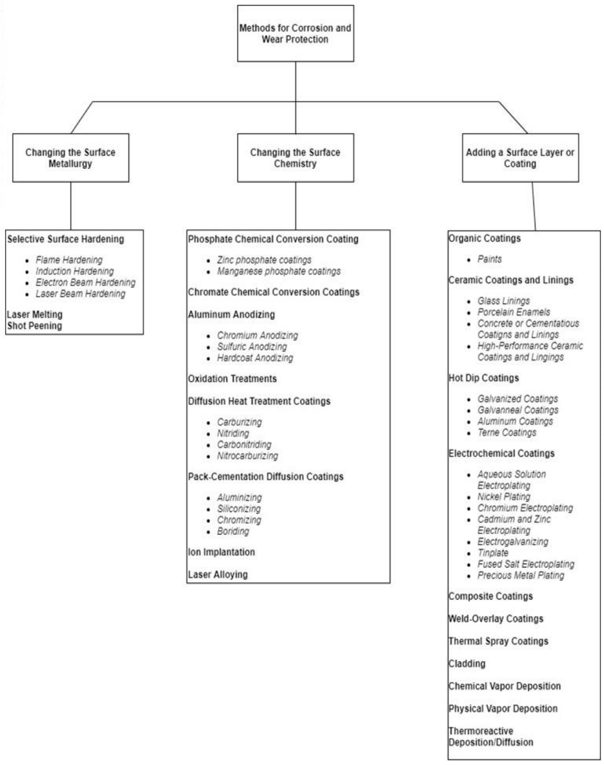

Figure 2. Classification of surface treatments used to improve the wear and corrosion resistance of steels [3].

2.1.1. HOT-DIP GALVANIZING

Figure 3 shows steel parts after galvanizing applications and a galvanized surface. In the year 2013, over 7.5 million tons of steel were coated with the hot-dip galvanizing method in the European Union.

Hot-dip galvanizing has three main steps; cleaning the base material, fluxing the coating material, and dipping of coating material. Before dipping the steel is annealed to gain desired surface properties and to activate the surface for the dipping process. The conventional bath temperature for hot-dip galvanizing is between 440-460ºC [10]. Effective parameters in hot-dip galvanizing are bath temperature, dipping time, withdrawal speed, and bath composition. The most common additives for galvanizing baths are Al, Mg, and Ni.

Hot-dip galvanizing changes the surface chemistry and metallurgy of steel by creating new phases on the surface such as the Γ, δ, ζ, and η phases of zinc-containing iron [11]. These phases are lined up from the steel surface to the outer surface respectively. The Iron content of these phases decreases from the inner to the outer surface (Figure 4).

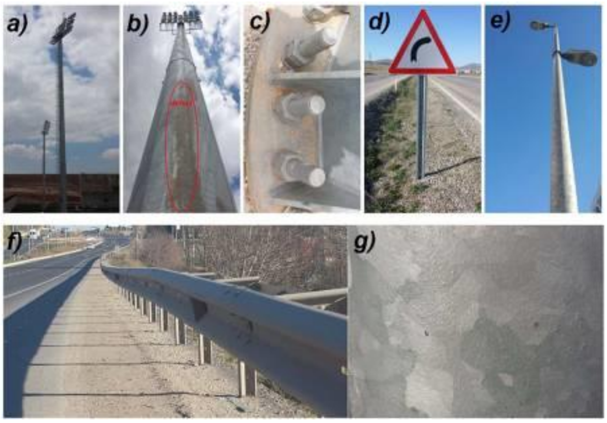

Figure 3. (a) A pole, (b) defect of galvanized part, (c) nuts and bolts, (d) a sign, (e) lampposts, (f) motorway barriers, and (g) a galvanized surface [9].

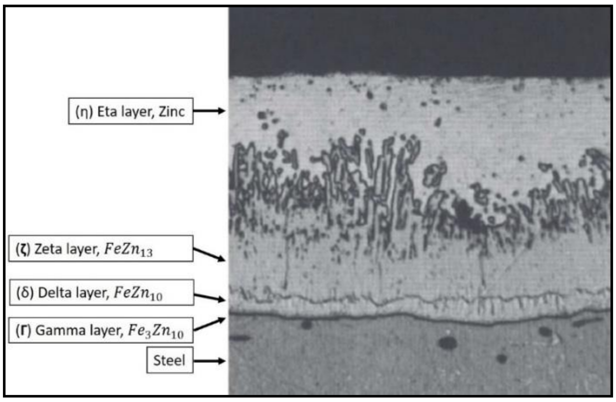

Figure 4. A micrograph of hot-dip galvanized steel [11].

The effects of Mg and Al addition to the hot-dip galvanizing bath have been investigated in the literature. Xie et al. (2018) studied the effect of Mg content on galvanization baths. Dissolution of Mg in the lattice structure of intermetallic compounds inhibits the growth of intermetallic phases. In addition, Mg segregates at grain boundaries and this promotes grain refinement. The effect of Mg content on the XRD results in the hot-dip galvanizing can be seen in Figure 5 [12].

Research studies have revealed that the steel composition has a significant influence on the performance of the hot-dip galvanizing process. Since steel is an alloy, it contains different alloying elements. During the hot-dip galvanizing process, the steel is corroded, and therefore there is an interaction between the alloying elements and the galvanizing bath. Depending on this interaction, the phase distribution of the layer to be obtained by the galvanizing process is affected and this effect manipulates the performance of the coating layer [13].

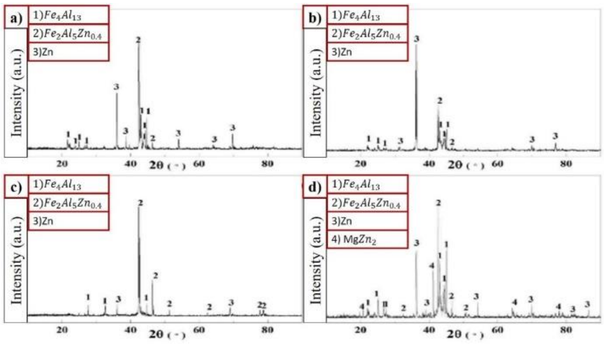

Figure 5. XRD patterns of the reaction layer of the Zn-Al-Mg alloy coatings with (a) 0, (b) 1, (c) 3, and (d) 5 wt. %Mg [12].

2.1.2 HOT-DIP ALUMINIZING

Hot-dip aluminizing is one of the methods used to improve the corrosion, wear, and oxidation resistance of steels [14]. As in other hot-dip processes, bath content, dipping time, temperature, and composition of the substrate are the most important factors affecting the coating performance in hot-dip aluminizing. The coating obtained by this method is in a three-layer structure and these layers are ordered from the inside out as the substrate material, Al-Fe intermetallic layer, and Al. Aluminum-rich intermetallic compounds are brittle and undesirable in the coating layer [14, 15].

Su et al. (2008) studied the effect of time and temperature on the hot-dip aluminum process. According to the study different coating structures have been obtained in different variations of dipping temperatures and dipping times. Increasing dipping time and the temperature had the effect of increasing the thickness of the intermetallic layer [15].

Numerous studies have been carried out including comparative studies to determine and understand the wear behavior of hot-dip aluminized steel. Qiu-yu et al. (2015) investigated the dry sliding wear behavior of hot-dip aluminized AISI H13 steel. To improve the elevated temperature wear resistance of this steel grade, hot-dip aluminizing is a significant option thanks to the intermetallic phases that have fine thermal properties. Qiu-yu et al. (2015) studied the wear rate of aluminized and uncoated steel as a function of load and temperature. In their study, they discovered that hot-dip aluminized H13 steel had better wear resistance under load than uncoated steel at high temperatures, whereas uncoated steel had better wear resistance under load at room temperature [16].

2.2. ELECTROCHEMICAL COATINGS

The electrochemical coating is a surface treatment in which an electrolysis cell is used for the coating process and the material to be coated is immersed in this cell as an electrode. Depending on the potential difference, it is possible to obtain metal, alloy, cermet or composite coating on the material surface to be coated with materials carried from the electrolyte and the counter electrode [17]. Electrochemical coatings, in which the wear and corrosion resistance of steel parts can be increased, can be applied with aqueous solutions at room temperature or with molten metal salts at high temperatures [18]. Surface cleaning and preparation processes, which may be alkaline, acid, or electro-cleaning methods, are important to increase the adhesion of the coating/substrate interface and thus improve the method's contribution to corrosion and wear resistance [19]. In addition, as in decorative chrome plating applications, intermediate coating layers can be used to strengthen interfacial adhesion or increase corrosion resistance (for example, steel/copper/nickel/chrome instead of steel/chrome). The properties of the coating layer obtained by the electrochemical method are determined by the variations of the variables such as bath composition, bath temperature, current intensity and regime, and immersion time [20]. Since the electrochemical coating process is carried out at relatively low temperatures when applied with aqueous solutions, it does not cause metallurgical phase changes or distortions and is preferred for coating steels to be used in some special applications. Due to the nature of the process, it is very difficult to ensure the uniformity of the coating layer. Moreover, if the cathode efficiency is less than 100% in the electroplating process, hydrogen gas is produced. Hydrogen gas adversely affects the properties of coatings. However, hydrogen formation and related negative effects can be prevented by the use of suitable agents such as boric acid [21, 22]. The process parameters are flexible so that they can be adjusted according to the desired hardness and coating thickness.

A variety of metals, including nickel for the automotive industry and consumer products or on pistons and cylinder walls, chromium for hard coatings to improve wear resistance, cadmium, and zinc to improve corrosion resistance, can be electroplated on steel substrates. This method can also be used to coat precious metals such as silver and gold [23].

2.2.1. COPPER ELECTRODEPOSITION

Copper is a highly preferred electrochemical coating material due to its high electrical and thermal conductivity and relatively low price. In addition, it is quite easy to coat copper with the electrochemical method [23, 24]. Copper can be coated on substrates with several methods such as PVD, CVD, electrodeposition, and electroless deposition. Electrodeposition has various advantages among these methods such as higher current efficiency, adequate thickness, porosity-free structure, good adhesion, deposition rate, and cost [24]. There are several copper plating baths namely sulfate bath, phosphate bath, and chloride bath. Among these baths, acid-based sulfate baths have several advantages like uniformity in strength, fast deposition, lower toxicity, and cost. The properties of copper coatings formed by the electrochemical method are dependent on process parameters such as bath composition, processing temperature and time, current density, and current regime [23]. It is possible to change the properties of the copper layer coated by the electrochemical method with the use of various agents. For example, fine-grained nanoparticles with high adhesion can be coated with a lactic acid supplemented sulfate bath [25].

2.2.2. NICKEL ELECTRODEPOSITION

Nickel is a preferred electrochemical coating material in almost all industries due to its contribution to the wear and corrosion resistance of steel. In addition, providing a visually desirable appearance is one of the reasons for preference. The engineering properties of the nickel plating layer obtained by the electrochemical method depend on parameters such as bath composition, temperature, immersion time, current intensity, and regime, as in other electrochemical coatings. It is also possible to improve the performance of nickel coatings with additives such as sodium dodecyl sulfate, sodium chloride, ethanol, and propanol [26]. Zhao et al. (2007) has investigated the current density effect on microstructure. They reported that grain size increases with increasing cırrent density during electrodeposition [27].

2.2.3. CHROMIUM ELECTRODEPOSITION

Electrochemical chromium plating is a preferred surface treatment because it is chemically inert, resistant to high temperatures, and has superior corrosion and wear resistance. Chromium can be applied with the electrochemical method for decorative or protection purposes. The differences between decorative applications and protection applications are the thickness of the coating layer and the intermediate layer coatings. While hard chrome plating for protection is applied directly to the steel surface, there are interlayer coatings such as copper and nickel in the decorative chrome plating method [28]. Current efficiency is around twenty percent due to hydrogen formation in electrochemical chrome plating [26]. From the past to the present, chrome plating has been done with hexavalent chromium, but due to the negative effects of hexavalent chromium on the environment and human health, many studies have been made and continue to be made on the use of trivalent chromium in chrome plating [29].

Post-treatment can be used to manipulate the engineering properties of electrochemical chromium coatings. According to a study by Li et al. in 2017 [29], electrodeposited chromium on #45 carbon steel from a trivalent chromium bath performs different hardness values with different heat treatments. As can be seen in Figure 6 with increasing heat treatment temperature obtained hardness value increases.

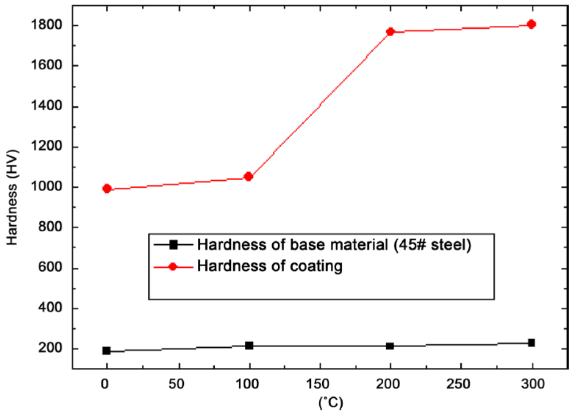

Figure 6. Effect of heat treatment on the hardness of hard chromium plating [29].

2.3. ELECTROLESS COATING

The electroless coating is a coating method that offers excellent coating uniformity, corrosion resistance, wear resistance, and high hardness, and is performed with a controlled reduction reaction. Nickel, Ni-P, and Ni-B coating applications are generally performed with this method. Due to the previously mentioned features, it is used in almost every field of industry [30]. Variables such as bath composition, bath temperature, and pH have high importance in the formation of the properties of the coating layer obtained in the electroless coating method [31]. There are two main baths for electroless coatings; acidic and alkaline baths. Ni and Cu are the most preferable electroless metallic coating elements due to their properties according to the literature. Nickel chloride or nickel sulfate is the main nickel ion source. Copper sulfates, acetates, and nitrates are used for Cu plating as ion sources. In addition, the alloys for the electroless coating method may contain Co, Pd, Pt, Au, or Ag [32]. In electroless composite coating particle characterization gains importance as an effective parameter. The particles used in composite electroless coating contain oxides, carbides, ceramics, boron, diamonds, and polymers. The coating properties can be tailored by adjusting the bath composition and particle distribution. In addition, heat treatment can be used to gain desired coating properties.

2.4. THERMOCHEMICAL SURFACE TREATMENTS

The wear resistance, fatigue strength, and corrosion resistance of steel can be improved by changing the surface chemistry as a result of the surface treatment processes applied to the surface of these materials [33]. Since the change of surface chemistry in thermochemical surface treatments occurs by atomic diffusion, the chemical composition, lattice structure, and diffusion coefficient of the substrate are the main factors affecting the process efficiency [34]. In thermochemical surface treatments, elements such as C, N, and B, that have very small atomic diameters, are generally used to harden the surface. However, Al, Cr, Ti, and V are also used in some surface treatment methods. The most commonly used thermochemical surface treatments are carburizing, nitriding, carbonitriding, nitrocarburizing and boriding [35].

2.4.1. CARBURIZATION

Steels containing less than 0.2% C are insensitive to heat treatment applied for hardening. The process of carbon diffusing to the surface of such steels in carbon-rich environments is called carburizing. This process is carried out at a temperature of approximately 850 ºC-900 ºC and the carbon content on the surface is increased to around 0.8-0.9%, making the steel responsive to the heat treatments. After carburizing, with quenching and tempering steps, materials with a hard surface and ductile core are obtained. Carburizing can be carried out in solid, liquid, gas, and plasma environments, but a gas atmosphere is generally preferred for the carburizing process [36, 37].

Arulbrittaraj et al. in 2016 [38], reported the carburization process has an important effect on the surface hardness of steels. The hardness measured on the surface after the carburization process was 423 HV, and the hardness value gradually decreased towards the material core and took the value of 220 HV in the core [38]. Agarwal et al. (2007) investigated the effect of temperature in the carburization of 316L stainless steel material. They stated that the surface hardness obtained with relatively low-temperature carburization was three times higher than that of the steel core. In addition, they argued that residual compressive stresses on the material surface obtained by carburizing improved the wear and fatigue strength and changed the fracture starting point [37].

Izciler and Tabur (2006) found that increasing carburization time increases diffusion depth which improves wear resistance and hardness of steel. In addition, increasing the carburizing time reduces the amount of residual austenite remaining in the structure and decreases its size [36].

2.4.2. NITRIDING

The nitriding process is a surface hardening method in which nitrogen diffuses to the surface of the material at temperatures between 500-550 °C. Minimal distortion and excellent dimensional control are possible due to relatively low temperatures and no need for quenching. However, the steels to be nitrided should be quenched and tempered before nitriding. The process can be carried out in gas, liquid, and plasma environments. High surface hardness, wear resistance, fatigue resistance, and corrosion resistance can all be obtained through the nitriding process. The depth of the nitride layer in this method is affected by processing time, temperature, nitrogen activation, and steel composition. The nitrided surface is made up of diffusion layer and compound layer. While the diffusion layer consists of the addition of nitride precipitates to the internal structure of the base metal, the compound layer part consists of ɣ and ε layers. The compound layer seen as white is hard and brittle and it does not react with the etching reagent during metallographic preparation. Steels containing Al, Cr, V, W, and Mo are quite suitable for nitriding since they already contain stable nitride at the nitriding temperature [39]. Kikuchi et al. (2010) studied the effect of fine particle peening on gas nitriding using stainless steel backing material. They reported that the nitriding layer formed by the nitriding process applied to such materials is quite thin due to the passive layer on the stainless steel. They suggested that peening made before the gas nitriding process facilitates the diffusion of nitrogen atoms to the surface by forming a stratification on the surface of the stainless steel, thus improving the fatigue strength [40]. Menthe et al. (2000) investigated the effect of plasma nitriding on the mechanical properties of 304L stainless steel material. They stated that the microhardness value increased from 3.3 GPa to 18 GPa, the wear rate decreased, and the residual compressive stresses that improved the fatigue strength increased [41]. Podgornik et al (1998) investigated the effects of plasma nitriding and pulse plasma nitriding on the tribological properties of AISI 4140 steel. They stated that the surface hardness increases with the increased nitrogen content. The $HV_{0.5}$ hardness values were changed to nearly 625 HV, 725 HV, 720 HV,975 HV, and 950 HV for hardened, 17 hours pulse plasma nitrided, 17 hours plasma nitrided, 28 hours pulse plasma nitrided, and 28 hours plasma nitrided samples, respectively. It was observed that pulse plasma nitriding provides the same case depth in a shorter time compared to conventional plasma nitriding. Furthermore, they proposed that the hard and brittle compound layer formed on the surface as a result of nitriding has a negative impact on wear resistance due to the formation of hard abrasive particles during sliding [42]. As a result, the formation of the hard and brittle compound layer must be controlled.

Genel et al. (2000) in their study on the effect of ion nitriding on the fatigue strength of AISI 4140 steel. They found that as the case depth increases, the fatigue strength increases, the case depth is time-dependent, ion nitriding provides 50% better fatigue strength than tempered martensites and the residual compression stress increases as the case depth increase, and this positively affects the fatigue strength [43]. Gas nitriding is performed in an ammonia gas environment. Liquid nitriding is a thermochemical surface treatment performed in molten salt baths consisting of nitrogen-carrying cyanide and cyanates. Since the process takes place at relatively low temperatures, dimensional stability is high. Because nitrogen solubility in the ferrite phase is higher than carbon solubility, the nitriding processes that take place at low temperatures where the ferrite phase is stable ensure that the structure is rich in nitrogen [44]. The plasma nitriding method is a thermochemical surface treatment where active nitrogen is sent to the steel surface using glow discharge technology to achieve diffusion. Nitrogen ions are sent to the material surface using a vacuum environment and high voltage electricity. Ion bombardment heats the steel surface, cleans, and provides active nitrogen. In the plasma nitriding method, the controllability of case chemistry is higher and the possibility of distortion is very low [45].

2.4.3. CARBONITRIDING

Carbonitriding is a thermochemical method in which the carbon and nitrogen atoms are diffused simultaneously to the steel surface at temperatures where the austenite phase is stable. Carbonitriding makes the steel surface suitable for quenching. This operation is a modified form by adding ammonia to the atmosphere used in the gas carburizing method. While nitrogen increases the hardenability of steel, it also reduces the risk of deterioration and cracking. Surfaces obtained by carbonitriding are harder than surfaces obtained by gas carburizing. In addition, carbonitriding is carried out at lower temperatures and a shorter time than gas carburizing. The carbonitriding method is suitable for steels with a carbon content of up to 0.2% [46].

2.4.4. NITROCARBURIZATION

The nitrocarburizing process, which is applied at temperatures where the ferritic phase is stable, is a thermochemical surface treatment in which nitrogen and carbon atoms are diffused on the steel surface at the same time. Steel surfaces with high wear, fatigue, and corrosion resistance are obtained by this technique. In the ferritic phase, the solubility of nitrogen in the matrix is higher than that of carbon, and therefore temperatures at which the ferritic phase prevails are preferred. The process can be carried out in solid, liquid, gas, and plasma environments. The steel surface obtained with the nitrocarburization process consists of a 10-20 μm thick HCP-structured carbonitride layer and a diffusion layer just below this layer [47].

Wen (2010) reported that the nitrocarburization process increases the hardness of the steel and lowers the friction coefficient, decreasing the erosion rate and wear loss. In addition, it was observed that the anti-abrasion properties improved with the increase of the diffusion depth [48]. With the nitrocarburizing process, the wear mode of the material has changed from adhesive to abrasive. Zhang et al. (2011) stated that the fatigue strength of nitrocarburized 35CrMo steel improved between 35% and 51%. They investigated the mechanical properties of nitrocarburized M50NiL steel. In addition, they observed that the hardness of the nitrocarburization layer increased with the increasing process temperature [47].

2.4.5. BORONIZING

Boronizing is a thermochemical surface treatment where hard boron compounds are obtained by diffusing boron atoms on the steel surface. Boronized surfaces are very hard and have low friction coefficients, high temperature, and corrosion resistance. This operation is carried out at 900 ºC - 1100 ºC degrees, under solid, liquid, gas, or plasma conditions. Boronizing can be applied to many different material types such as alloyed or unalloyed steels, cast irons, non-ferrous metals and alloys, powder metallurgy products, and cermets. FeB and Fe_2B intermetallics formed by boron with iron are hard and brittle, while Fe_2B is relatively soft and ductile. Among the boronizing methods, the most common method is pack boronizing. Pack boronizing is applied to small-sized parts and boron or boron carbide is used in the packing process. The control of the pack boronizing method is difficult and its automation is not possible. This process includes boronizing agents, activators, and oxide reducing steps. Liquid boronizing is carried out in melt salt baths containing B_4C, BaO, and NaCl. Liquid boronizing results in a layer with a thickness of 100-200 µm. The gas boronizing process is a thermochemical surface treatment performed by applying the steam obtained by the thermal splitting of boron hydrides to the steel surface. It is possible to obtain a more homogeneous diffusion layer by increasing the temperature. It is a preferred method for hardening complex shaped parts. Homogeneous surface hardness can be obtained [49,50].

Tabur et al. (2009) stated that the surface hardness of boronized steel increases approximately nine times the surface hardness of the substrate material. In addition, it was observed that the FeB layer was harder and more brittle than the Fe_2B layer, and the boronized layer thickness increased with increasing processing temperature and time [49]. Ozbek and Bindal (2002) researched the mechanical properties of boronized AISI W4 steel. They observed that the boride layers consist of three different regions: boride layer, transition zone, and matrix. While a single-layer structure consisting of Fe_2B was observed during the period of up to four hours, the structure consisting of FeB and Fe_2B was observed in processes longer than this process. Interphase cracks were observed in boride layers thicker than 300 µm. In addition, the fracture toughness of Fe_2B is four times higher than FeB [51].

2.5. PHYSICAL VAPOR DEPOSITION

The physical vapor deposition method is a surface treatment in which the coating material is obtained by evaporation from a liquid or solid source, followed by condensation on the surface of the material to be coated. Coating thicknesses with nanometer precision can be obtained in PVD applications. The controllability of the coating thickness at such a precise level makes the PVD method preferred in the microelectronics and machining tool industries. As in all coating methods, cleaning the surface material to be coated is important in terms of improving adhesion in the PVD method [53]. Since the PVD method makes it possible to produce multi-layer coating, it allows for an increase in the hardness, wear, and corrosion resistance of the coating layer in this way [52]. The application allows the use of reactive gases and, as it is possible to form oxides and nitrides in this way, it is possible to produce very hard anti-wear coatings. Examples of hard coatings are TiN, TiAlN, and CrN [54]. The method can be applied in different ways. As shown in Table 1, application methods differ in terms of how the coating material is obtained [50-54].

Table 1. The methods of PVD coating technique [50-54]

Methods	**Method of Obtaining Coating Material**
Evaporation	Evaporation from the target material.
Sputter Deposition	Physical scattering from the target material.
Arc Vapour Deposition	High current-low voltage application on electrodes
Ion Plating	Any of the methods aforementioned.

PVD application methods offer several advantages and disadvantages. While the vapor evaporation method is quite simple and inexpensive, the target materials are expensive and heat removal costs are in question in the sputter deposition method. Likewise, while arc vapor deposition removes the restriction on the positioning of the material to be coated during the coating, uniformity and residual stresses pose problems in the ion plating method [50-54].

2.6. CHEMICAL VAPOR DEPOSITION

Another coating method carried out in the vapor phase is the chemical vapor deposition method (CVD). The CVD method is a method that is frequently used in industries where high technology is desired such as semiconductors and optics, as it enables the coating of products with complex geometrical properties, and does not require a sensitive ultra-vacuum atmosphere, and allows rapid coating. However, the fact that the process is carried out at relatively high temperatures (600ºC and above) is one of the factors limiting its use [57].

2.7. SOL-GEL COATINGS

Ceramics are hard and corrosion-resistant materials. The sol-gel coating method is a surface treatment developed for coating steels with ceramics. In this process, the coating solution is prepared, and transformed into gel via heating; the material is dipped in this gel and the coating is sintered. It is possible to obtain multi-layer coatings and improve the coating performance by performing the dipping process more than once [59]. The sintering temperature is a parameter that affects the wear and corrosion resistance of the coating. It has been reported that different corrosion and wear resistance are obtained by changing the sintering temperature by Ruhi et al. [60].

2.8. THERMAL SPRAY COATINGS

Spray coating methods are surface treatments performed by striking powder coating materials on the steel surface at high speeds. It is possible to use various materials, from refractory metals to composites, as coating materials in spray coating applications where relatively thick coatings are obtained. The various thermal spray coating methods are shown in Table 2 [57].

Table 2. Spray Coating Methods [57]

Spray Coating Methods
Warm Spray
High-Velocity Air Fuel
Wire Arc Spraying
Plasma Spray
High-Velocity Oxyfuel
Cold Spray
Flame Arc Spray

It is possible to produce boride-containing coatings with arc spray coating, which is one of the thermal spray methods. Amushasi et al. obtained a coating layer consisting of Fe_2B, α-Fe, and FeB in their study using St52 substrate material [61]. Al-Mangour et al. in their study, in which they applied the cold spray method to produce biomaterials, revealed that dense coatings with high corrosion resistance could be obtained with the cold spray method [62]. The surface properties of steel can also be designed with the HVOF process. Cr_3Cr_2-NiCr is a suitable coating layer to improve the surface properties of carbon steel. Akhtari-Zavareh et al. in 2015 [63], studied Cr_3Cr_2-NiCr ceramic coatings obtained with HVOF sprayed on carbon steel. They have found that tribological and electrochemical properties of carbon steel increased with HVOF sprayed Cr_3Cr_2-NiCr ceramic coatings [63].

3. CONCLUSION

Steels are one of the cornerstones of industrial production due to their superior properties but wear and corrosion limit the use and life of steels. Various surface treatments are applied to steels to prevent or minimize the destructive effects of corrosion and wear. Corrosion and wear can affect steel materials separately as well as deform them in combination. Therefore, while taking protective measures, it is important which phenomenon influences the steel. A hard chrome coating, for example, would be appropriate to apply to the surface of a steel part vulnerable to wear, whereas hot-dip galvanizing would be appropriate to prevent corrosion. The operating temperature of the relevant part is also effective in prescribing preventive surface treatments. A hot-dip aluminized steel part, for example, is more resistant to wear at 600 ˚C than at room temperature. The composition of the steel to which the protective measures will be applied is also an important factor in the selection of protective measures. For example, the steel composition affects the phases formed during galvanization. An important consideration in the choice of preventive surface treatments is the uniformity of the coating. While nickel can be coated by electroplating and electroless methods, electroless nickel coating provides the best uniformity. Preservation of the structural properties of steel materials is also an important element in choosing preventive surface treatments. Although methods such as PVD and CVD have advantages such as speed and allowing various material combinations, they cannot be preferred for coating steels to be used in some applications due to process temperatures.

The performance of surface treatments can be improved by various methods. For example, corrosion and wear performance can be improved with secondary or tertiary reinforcements in surface treatments. Electroless Ni-P and cold sprayed Co-Cr are examples of this situation. In electroplating, it is possible to obtain better corrosion and wear resistance by designing parameters such as current regime and density, bath composition, and temperature. Multi-layer production of coatings is also a method that can be applied to obtain superior wear and corrosion resistance. Surfaces with superior properties can also be obtained through the combination of surface treatments. For example, gun barrels must have both high fatigue strength and resistance to corrosion and wear due to the task they undertake. These properties expected from barrels can be achieved by combining nitrocarburization and hard chrome plating.

As a result, engineers and researchers working on wear and corrosion have many surface treatment options to prevent wear and corrosion, which negatively affect the usage area and service life of steels. Which of these methods will be used may vary depending on the working environment, the material being worked on, and the performance expected from the material. Although each method has its advantages and disadvantages, these disadvantages can be eliminated by options such as secondary reinforcements, heat treatment, and parameter change, or a combination of surface treatments for the development of protective measures. Since the development process of protective measures continues, it can be said that the problems caused by corrosion and wear will be at lower levels in the future.

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DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declares that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Ugur Temel YILDIZ: Conceptualization, Writing - original draft, review & editing.
Temel VAROL: Supervision, Writing - original draft, Project administration.
Gençaga PURÇEK: Methodology, Supervision.
Serhatcan Berk AKCAY: Review & editing.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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