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Sustainable carburization of low carbon steel using organic additives: A review

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ABSTRACT

Mild steel is made of iron and other elements, the chief among which is carbon. It is considered one of the most notable alloys in engineering applications because of its high tensile strength advantage and low cost. However, mild steel essentially lacks the hard surface quality which is considered key to many structural and industrial applications. This review explores various aspects of the carburization of mild steel which is targeted at providing the hard surface quality it lacks. This work critically reviews the mechanisms of different carburization methods, factors affecting carburization quality, and the potential of organic additives for carburizing low-carbon steel. Furthermore, this review article provides new insights into organic energizers and their benefits to both the handlers of carburizing operations and the environment in which they are carried out, following the United Nations' Sustainable Development Goal number 12 on sustainable production and consumption. Finally, this review concludes by providing directions for future research on organic additives-based mild steel carburization.

1. Introduction

Iron is ranked only second to aluminum in the hierarchy of the most abundant metallic elements in the earth's crust [1]. These two elements have become the most commonly used structural metals with iron taking the more pre-eminent position. This is partly because of reduced energy requirements during extraction from its ores and also owing to the wide range of properties its alloys offer. Mild steel, one of such impressive alloys, is made of iron and other elements, chiefly carbon, and is considered the most important material because of its high tensile strength and low cost. This makes it most suitable for general engineering applications. Like other steels, the high iron content gives mild steel its ferrous and magnetic nature (hence ferromagnetic) and a relatively high melting point of between 1450 °C and 1520 °C [2]. However, mild steel lacks the hard surface properties required in some applications. Hence, the option for surface modification where a combination of tough/soft core and hard surface is desirable [3–8]. This results in coating of various types among which is carburization because the strength, surface treatment, and hardness of low-carbon steel cannot be improved only by conventional heat treatment [9].

The carburization process, which takes place in two key steps, occurs when low-carbon steel is brought into close interaction with a solid, liquid, or gaseous carburizing medium at an austenitic temperature range: releasing free carbon through chemical reactions [10]. These free carbon atoms are rapidly diffused into the surface of steel because of the large potential difference that exists between atmospheric carbon and

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steel surface following Fick's first law of diffusion [11]. The rate of absorption of additional carbon continues to decline as the surface becomes more and more saturated with carbon content until equilibrium is eventually reached; marking the end of the first step. The diffusion of carbon takes place in the second step between the surface and the core at a much slower rate as a result of the reduced carbon gradient between the two regions. It takes a shorter time for the first step to be completed which is then maintained for the succeeding process, the depth of which is dependent on the diffusion of carbon from the exterior to the interior part of the steel material. Carburizing is performed to obtain a surface with a carbon content of between 0.6 and 1.10% for steels that usually contain 0.1 to 0.25% carbon.

The engineering of materials' surfaces to enhance their life and functionality has generated intense interest among researchers and other stakeholders in the field. Appropriate thermo-mechanical surface treatments result in general rearrangements of atoms in metals and alloys with a corresponding clear distinction in physical, chemical, and mechanical properties [12]. Heat treatment processes such as immersion hardening, induction hardening, and case carburizing form parts of the very important surface treatment processes deployed to induce the desired improvements to materials' surfaces. Many metallic materials can be carburized to raise their effectiveness and functionality. The choice of which carburizing process to implement for specific applications follows the benefits accruable from such methods. Many carburized parts are processed by gas carburizing which is one of the most controllable methods in terms of regulation of effective depth of carbon, using carbonaceous gases. It is also the fastest method of carburization [13]. Liquid carburizing was reported to pose a salt disposal challenge and this makes it less desirable compared to gas carburizing [1]. However, for economic considerations, flexibility, as well as suitability for small machine parts, the pack carburizing process is preferred to the duo of gas and liquid carburizing [14]. Other types of carburizing methods include plasma and vacuum carburizing. All of these have varying degrees of temperature requirements and accuracy.

Romedenne et al. [15] investigated the degree of carburization of three different steel samples exposed to liquid sodium environment at 600 °C and 650 °C. A larger amount of diffused carbon was observed in strain-hardened AIM1 steel than in 316 L annealed steel. This was attributed to the higher density of dislocations. These defects, in addition to the presence of grain boundaries, could have triggered a faster conversion of M23C6 into M7C3 carbides. In another study on gas carburizing, Oh et al. [16] infiltrated the surface of cold-forged chromium alloy steel with carbon from propane (C_3H_8) gas. Maintaining carburizing gas volume flow rate at 350 m^3/h and other carburizing parameters, the hardness gradient of the carburized layer was found to increase as the carbon content of the material decreased. Various research findings regarding the successful use of inorganic carburizers to achieve good surface hardening of ferrous metallic parts have been reported in the literature [17–21]. Romedenne et al. [15], deployed inorganic carburizing sources for the precipitation of carbides on the surfaces of alloys, while Arthur and Azeko [22], on the other hand, opted for organic carbon additives. In a bio-cyaniding work on ferrous materials, they used cassava leaves as a source of cyanide because of their rich cyanide content. Similarly, Umunakwe et al. [23] used carburizing powders from palm kernel and coconut shells in a pack carburizing procedure to carburize steel with significant success. The reports were akin to an earlier one by Syahid et al. [14] who successfully improved the fatigue strength of low-carbon steel through the use of a carburizing process in the media of coconut shell charcoal and shell powder as a catalyst.

Certain post-carburizing processes are also often carried out to improve the properties of the carburized surfaces, chief among which is shot peening. Wu et al. [24] described shot peening as a mechanical strengthening method of carburized surfaces which is widely used to improve fatigue strength of gear, bearing, crankshaft, and other mechanical components due to its high efficiency and low cost. In a study of the catalytic effect of shot peening pre-treatment on the plasma nitriding process, Unal et al. [25] found that the process could promote nitriding efficiency and increase the thickness of the white layer, thereby ameliorating the pay-off of nitriding. Similarly, Tang et al. [26] had earlier posited that pre-laser shot peening treatment is an excellent promoter of the adsorption of nitrogen atoms under the same plasma nitriding process, thereby improving the depths of composite layer and effective hardening layer. Amanov [27] cited laser shock peening, and ultrasonic peening as other surface engineering technologies that can as well improve the adhesion strength between the coating and substrate.

In a more detailed study on the effect of shot peening coverage on residual stress and surface roughness of 18CrNiMo7–6 steel, Wu et al. [28] found that the gap between the axial and tangential residual stress is reduced by shot peening. They concluded that an increase in coverage from 100% to 400% favors a corresponding increase in the surface residual stress from 628 MPa to 705 MPa while surface roughness parameters reportedly decrease with full coverage conditions. Ren et al. [29], x-rayed the effect of laser shock peening and carbonitriding on tribological properties of 20Cr2Mn2Mo steel alloy under dry sliding conditions. Parameters like surface roughness and microhardness as well as the coefficient of friction improved laser energy and several impacts. However, with growing laser energy, the primary wear mechanism is said to change from abrasive wear to a combination of abrasive and adhesive wear. Kikuchi et al. [30] agree with earlier submissions that the fatigue limit of carburized steels treated with peening increased as the size of surface dents induced by peening decreased, while also corroborating the fact that a decrease in size supports the effect of residual stress on the fatigue limit.

This review explores the potential of carburizing low-carbon steel with organic additives. Studies in this field are fairly abundant but with a narrow scope. For instance, Arthur and Azeko [22] conducted a review on the surface hardening of ferrous materials via the use of in-situ diffusion of carbon and nitrogen from cyanide-based bio-processed cassava wastes and focusing on the effects of bio-cyaniding on the microstructure, micro−/nano-hardness, and wear properties of the bio-cyanided surfaces in the last decade.Although the studies were insightful, it was limited by their area of coverage. In another brief review, Manne et al. [31] presented different works on the effect of the various methods of nitriding on mechanical properties, phase changes, and corrosion resistance of AISI430 ferritic stainless steel. However, the works reviewed appear too few to inform a conclusion on the effects of nitriding on the properties of the material. Therefore, this study summarized different methods of carburization with examples that reveal specific challenges and resolutions with insightful backing for organic energizers which are less popular than their inorganic counterparts for carburizing low-carbon steel. This is despite being more beneficial in terms of cost and eco-friendliness. It is believed that this will contribute immensely to environmental safety by minimizing carbon emissions and promoting cleaner and responsible production, as well as consumption. The review focuses on the most recent studies with >70% of the studies carried out within the last 5 years.

2. Carburization methods

Different methods of carburizing mild steel are reviewed in this section to provide an understanding of how they relate to each other and affect the ultimate results of depth and quality of carburizing. Carburizing affects fatigue life by changing the chemical composition, microstructure, hardness, or residual stresses of the carburized mild steel. Carburization could also be supported by material modification processes such as shot peening, and surface rolling which are often used to introduce compressive residual stresses on steel surfaces to delay crack initiation and propagation consequently [32–34].