

ORIGINAL RESEARCH

Effects of surface hardening on hardness and tensile strength of locally manufactured feed mill hammers

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Received: 13th March, 2023 / **Accepted:** 23rd June, 2023

Published online: 27th November, 2023

Abstract

Animal feed is a major production cost of raising livestock and accounts for about 65 - 68 % of the total production cost, mainly ingredients and processing costs. During feed manufacturing, a hammermill is required for the grinding process to produce quality feed. However, the absence of durable hammers on the local market in Ghana and the high cost of imported hammers compels feed producers to resort to locally manufactured hammers which wear fast due to poor quality of the material. This study considers the application of two surface hardening techniques: (i) carburizing (charcoal and Barium Carbonate (BaCO_3) as activator) and (ii) carbonitriding (charcoal, NPK fertilizer as a nitrogen source and Barium Chloride (BaCl_2) as activator) in combination with three different quenching media (water, air and oil), to improve the material properties of locally produced hammermill hammers. The surface hardening experiments were performed at 900 °C for 3 h after which the samples were quenched. Tempering was performed afterwards at 160 °C for 1 h. Carbonitriding and water quenching treatment had the best effect on hardness and tensile strength of all the treatments. It yielded the highest surface hardness and tensile strength of 410.06 HV and 768.79 MPa, respectively, representing about a 218 % increase in hardness and a 47 % increase in tensile strength compared to the control sample, which were 128.92 HV and 522.41 MPa, respectively. The result implies hammers produced with this carbonitriding surface hardening and water quenched technique would have improved hardness and wear resistance compared to untreated hammers.

Keywords: Animal Feed, Hammermill, Surface Hardening Techniques, Hardness, Tensile Strength

Introduction

Animal feed is usually processed to improve palatability, digestion and absorption of nutrients by animals. The feed manufacturing process involves activities such as receiving of raw materials, grinding, batching and mixing with each stage of the process requiring some form of machinery for effective operation. Particle size reduction or milling is a critical activity in processing feed. Milling is a size reduction process of grinding grains into flour for meal (Kaul and Egbo, 1985; Kawuyo et al. 2014) and it is achieved by overcoming the interior binding forces through the application of mechanical forces to alter the grain structure thereby reducing the grain size.

Williams and Rosentrater (2007), reported that grain milling is as old as human history and the process of milling has evolved over time from the use of simple traditional means such as stones, mortar and pestle to the use of mechanically powered machines and complex facilities for milling. It has been reported that reducing the particle size of the grain in feed processing will improve the feed efficiency of a diet by 1.0 % to 1.2 % for every 100 μm reduction in corn particle size (Wondra et al, 1995; Kim et al., 2002). There are three main types of grain mills available, namely, plate mill, roller mill and

hammermill. The selection of the type of mill depends on the type of raw material and the scale of production. Each mill has its advantages and disadvantages however, the hammermill is the commonest equipment used for grinding grains in feed production (Moiceanu et al., 2012). According to FAO (2006), hammermills are the predominantly used mills in developing countries. The main components of a hammermill are hammers, screen or sieve and a rotor. The major cost components in the operation of hammermills are energy (electricity/fuel) and replacement of hammers and the screen. For the production of quality feed at an affordable cost for the poultry industry in Ghana, availability of durable and affordable hammers is key. Although the imported hammers are durable, they are expensive and not readily available on the local market in Ghana.

This has resulted in feed producers and poultry farmers in Ghana relying on hammers produced by local artisans to support their production activities although such hammers wear fast due to their poor material quality of the steel grade used. Such steel grade, often referred to as mild steel is low in carbon and has a carbon content usually less than 0.25 percentage weight (wt %). It is the most abundant grade of steel and the least expensive on the local market in Ghana. Due to its low carbon content and hence low hardness, it wears fast leading to an increase in the frequency in replacement of hammers thereby increasing the cost of feed production. The increased rate of replacement results in an increase in machine downtime which also contributes to an increase in the production cost of poultry feed in Ghana. The high incidence rate of wear of the hammers during feed production may also result in metal contamination of the feed, which could affect the health of the birds (Okoye et al. 2011).

According to Fadare et al. (2011), heat treatment is a technique used to alter the properties of materials to modify its response to external impact. It involves the controlled heating and cooling of solid material to obtain the specific properties suitable for an engineering application. According to Dossett

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and Boyer (2006), the application of surface hardening gives steel a hard and wear resistant surface while retaining a softer, tough core. In some cases, this technique is employed to cut down cost of buying expensive materials such as high carbon steel which has higher hardness for some engineering applications. Through surface hardening, much less expensive materials such as low carbon steels can be case-hardened to improve their hardness for the same purpose. Hardness of a material is the main factor that affects its wear resistance and an increase in surface hardness of mild steel enhances the materials' resistance to erosion and wear (Chowwanonthapunya *et al.*, 2020). Surface hardening through heat treatment techniques can therefore be achieved through simple processes that can be easily adapted by local artisans or producers to manufacture durable hammers with qualities similar to those of the foreign hammers imported into Ghana. This study, therefore sought to investigate the potential of applying surface hardening treatments to produce quality hammermill hammers from mild steel in Ghana through simple heat treatment processes.

Materials and Method

Study area

The study was carried out in Greater Kumasi, Ghana located at 6.6666 ° N, 1.6163 ° W. The laboratory experiments were carried out at the Laboratories of the Material Engineering Department of the College of Engineering at Kwame Nkrumah University of Science and Technology- Kumasi and the Material Analysis Laboratory of Tema Steel Company Limited in Tema in the Greater Accra Region of Ghana.

Heat treatments applied

The two surface hardening techniques employed in this study are pack carburizing and carbonitriding. These two surface hardening treatments were selected based on how easily the technique could be adapted in terms of complexity and availability of facility to be used by local producers (artisans) to produce beaters locally (Schneider *et al.* 2013)

Material

Mild steel bars were obtained from a local metal market in Kumasi. The chemical composition of raw material was analysed using the American Society for Testing and Materials standard test method (ASTM E-415-15) for analysis of carbon and low-alloy steel by spark atomic emission spectrometry.

Table 1 shows the chemical composition of the sample. The material falls under American Iron and Steel Institute (AISI 1020 steel) which has 0.17-0.230 wt % C, 0.30 -0.60 wt % Mn, ≤ 0.040 wt % P and ≤ 0.050 wt % S. The main material used is a plain carbon steel and is used for many engineering applications due to its low cost and ease of fabrication (Smith and Hashemi, 2006).

Experimental design and procedure

A factorial design of two factors (surface hardening method and quenching medium) with three replications each was used for the experiment. Six (6) treatments combination based on the surface hardening method and a quenching medium were used in addition to a control (untreated specimen). The treatment combinations and codes are shown in Table 2 and the procedure for each treatment is outlined as follows.

Pack carburizing

This technique involves heat treating metal in a carbon-rich environment to improve on its properties (Schneider *et al.*, 2013). The procedure used is outlined as follows:

i. Preparation of carbon-rich mixture

A mixture consisting of 4 parts of charcoal and 1-part Barium Carbonate (BaCO_3). The BaCO_3 was used as an activator to promote the formation of CO_2 . The charcoal used as carbon source was grounded and sieved with 1 mm² nylon mesh. An electronic balance was then used to measure 500g and 125 g of charcoal and Barium Carbonate (BaCO_3) respectively. The resulting mixture was used for all treatments involving carburizing.

ii Loading into steel box

The prepared specimens were carefully placed in a steel box and covered completely with the mixture. The container was then covered with a lid and sealed with fire clay to ensure a closed system was obtained to prevent undesirable reactions.

Table 1 Chemical composition of mild steel

Element	Fe	C	Mn	P	S	Si	Cu	Ni
wt %	98.76	0.171	0.445	0.011	0.018	0.135	0.181	0.109
Element	Cr	Mo	Ti	Al	Nb	Co	Sn	
wt %	0.046	0.093	0.002	0.011	0.001	0.010	0.008	

Table 2 Treatment combination and codes

Treatment	Surface Hardening	Quenching Medium	Code
1 (T1)	Carburizing	Water	CW
2 (T2)	Carburizing	Oil	CO
3 (T3)	Carburizing	Air	CA
4 (T4)	Carbonitriding	Water	NW
5 (T5)	Carbonitriding	Oil	NO
6 (T6)	Carbonitriding	Air	NA
7 (T7)	Control	-	C

iii. Loading into furnace

The container was then placed in the Vecstar TRF furnace to begin the carburizing treatment. The conditions used for the experiment were standard conditions for pack carburizing as described by Schneider et al. (2013) for low carbon steel. The experiment was set up at 900 °C for three (3) hours. At this temperature, the specimen is raised into the austenite phase region to facilitate the diffusion of carbon into the metal.

Carbonitriding

This surface hardening process was used to heat treat metal specimen in an environment rich in carbon and nitrogen to improve on its properties (Schneider *et al.* 2013). The procedure used is outlined as follows:

i. Preparation of carbon and nitrogen rich mixture

A mixture of charcoal, Polyfeed NPK fertilizer and Barium Chloride (BaCl₂) which was used as an activator to promote the formation of CO₂ and NO₂ was prepared using mixture ratio of 4:4:1 by weight. The charcoal used as carbon source was grounded and sieved with 1 mm² nylon mesh. An electronic balance was then used to weigh 350 g, 350 g and 87.5 g of charcoal, NPK 30:10:10 and Barium Chloride (BaCl₂) respectively. The resulting mixture was used for the experiment.

ii. Loading into steel box

The prepared specimens were carefully placed in the steel box and covered completely with the mixture. The container was then covered with the lid and sealed with fire clay to ensure a closed system was obtained similarly as in the carburizing experiment.

iii. Loading into furnace

The container was then placed in the Vecstar TRF furnace to begin the carbonitriding treatment. The conditions used for the experiment were standard conditions for carbonitriding as described by Schneider et al. (2013) for low carbon steel. The experiment was done at a temperature of 900 °C for 3 hours.

Quenching and tempering

All specimens were later quenched in either water, oil or air immediately after removing the specimens from the furnace in each experiment. The rapid cooling of the austenite phase results in the formation of martensite which increases the hardness of the material (Dagne, 2015). Tempering was performed after hardening to relieve stresses induced by quenching and also reduce the brittleness of the treated specimens. In this case,

a quenched steel is heated below the eutectoid temperature Dossett and Boyer (2006). All specimens were tempered under a temperature of 160 °C with a holding time of 1 hour. The surface hardening conditions used in the study is summarized in Table 3.

Hardness measurement

The hardness test was carried out in accordance with the ASTM E 92 - 17 standard test method using a Digital Micro-Vickers Hardness tester (Model RMHT-201). The hardness readings were measured at both the core and surface of each specimen. According to ASTM E384 - 17, Vickers hardness (VHN) is expressed as:

$$VHN = \frac{1.845P}{d^2} \quad (1)$$

where P is amount of load applied in kgf and d is the mean length of the diagonals impression in mm.

The procedure used to prepare the sample for examination is outlined as follows:

i. Mounting of Specimen: The specimen was mounted in polyester for examination. A spirit level was used to ensure the samples were mounted correctly. The polyester was allowed to harden before further activities were carried out.

ii. Grinding and polishing of specimen: Each specimen was grounded on silicon carbide paper in increasing fineness using MP-2B Grinder Polisher. The grades used are 100 mm, 220 mm 320 mm, 400 mm, 600 mm and 1200 mm. The wet grinding method was used for the process with



Figure 1 Setup for tensile strength analysis using PROETI: DI-CP/V2 tensile test machine

Table 3 Summary of surface hardening conditions

	Carburizing	Carbonitriding
Mixture Constituent	Charcoal: BaCO ₃	Charcoal: NPK fertilizer: BaCl ₂
Mixture Ratio	4:1	4:4:1
Soaking Temp.	900 °C	900 °C
Holding Time	3 hours	3 hours
Quenching Medium	Water (5 litres), Oil (5 litres), Air	Water (5 litres), Oil (5 litres), Air
Tempering Temp.	160 °C	160 °C
Tempering Time	1 hour	1 hour

water used as lubricant. The specimens were further polished on micro clothe using alumina (Al_2O_3) as lubricant.

- iii. Etching: The polished specimens were then etched in nital solution (2% Nitric acid and 98% ethanol). The specimens were dipped in the etchant for about 10 seconds and then rinsed with distilled water. The specimens were then dipped in ethanol and allowed to dry.

Tensile strength measurement

The ASTM E8 - 13 standard for determining tensile strength of materials was used to determine the tensile strength of the treated and control specimens. The PROETI: DI-CP/V2 tensile test machine embedded with a computer and a printer was used for the tensile strength test. The resulting values and graphs were printed out for analysis.

Data analysis

The data collected from the experiment were subjected to ANOVA test at a significance level of 5 % using MATLAB R2016b software. The results are presented in graphs and tables.

Results and Discussion

Effect of surface treatment on material hardness

Figures 2 and 3 show a graphical presentation of the mean hardness values obtained at the core and surface of the samples respectively. The hardness test results showed significant increase in the hardness of the hammers at the surface and the

core. All treatment combinations (hardening technique in addition to quenching medium) yielded a higher hardness value compared to the control (untreated hammer). On core hardness, the specimen prepared under T4 (carbonitriding with water quenching) recorded the highest value of 175.08 HV while the control specimen, T7, recorded the least hardness value (106.06 HV). A similar trend in hardness levels was also observed for the surface hardness. Samples prepared under T4, again recorded the highest hardness value (410.06 HV) while the control (T7) recorded the least surface hardness value (128.92 HV).

The resulting increase in hardness of specimen surface treated compared to the untreated sample is due to the quenching of the carbon-rich surface layer which formed a high-carbon martensitic case as reported by Krauss, (1980). A similar trend as observed by Aramide *et al.* (2010) indicates that carbon enrichment in carburized steels accounts for increase in hardness compared to as received samples. All specimens with carbonitriding treatment recorded higher hardness values at the core and the surface compared to carburized steels with respect to the quenching medium used except surface hardness of the carburized-air quenched steel which recorded a higher hardness value than the hardness of steel with carbonitriding treatment. This trend observed is attributed to the presence of nitrogen absorbed during carbonitriding which lowers the critical cooling rate of the steel, thereby increasing the hardenability of the case in carbonitriding than in carburizing for the same steel (Fuller, 2013).

The ANOVA results of variations between means of treatments for core and surface hardness are shown in Table 4 and Table 5 respectively.

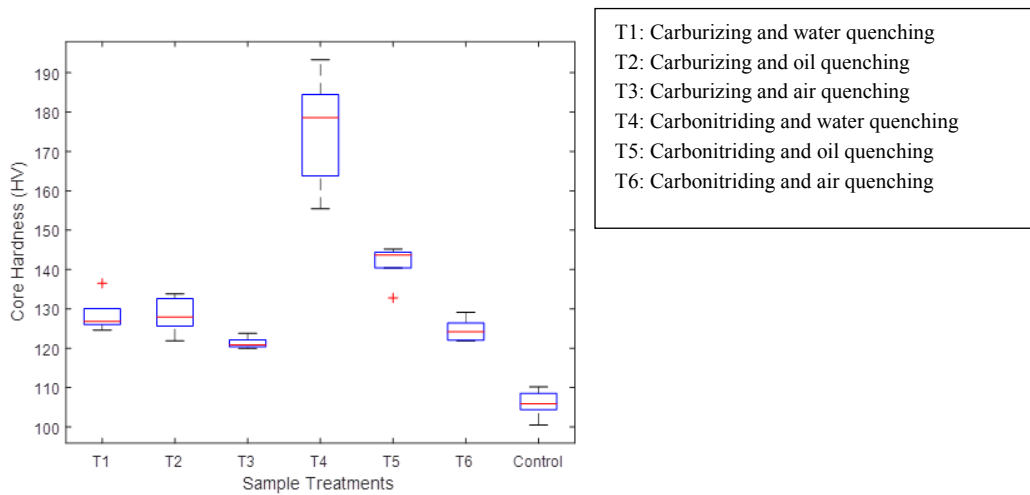


Figure 2 Boxplot of core hardness for the various treatments

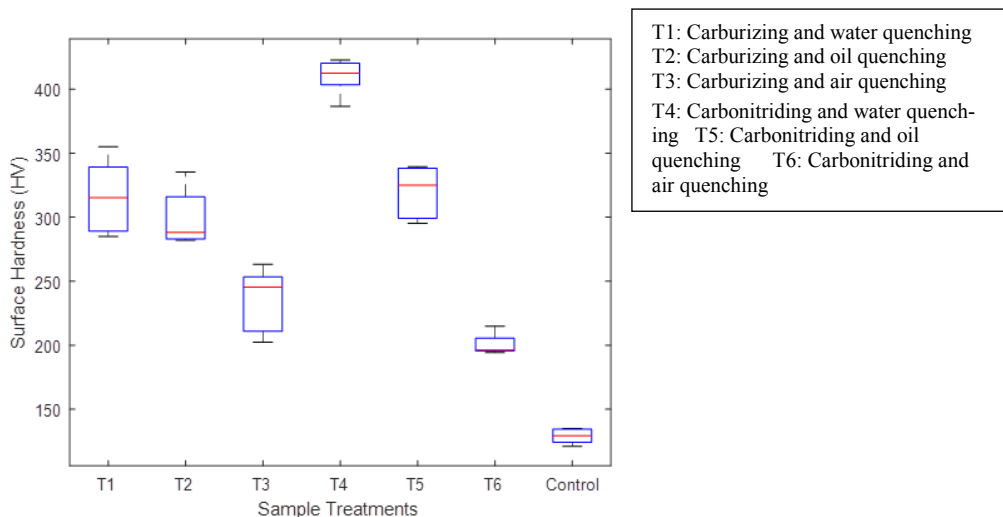


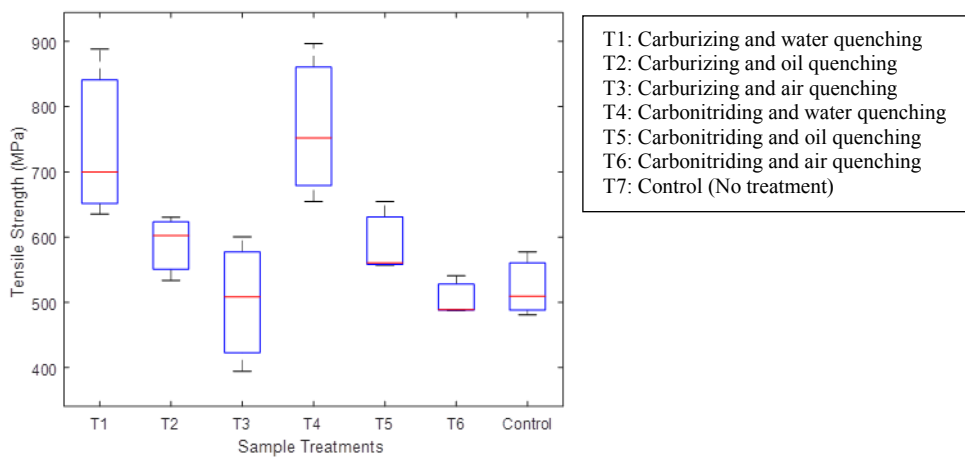
Figure 3 Boxplot of surface hardness for the various treatments

Table 4 Analysis of variance of core hardness

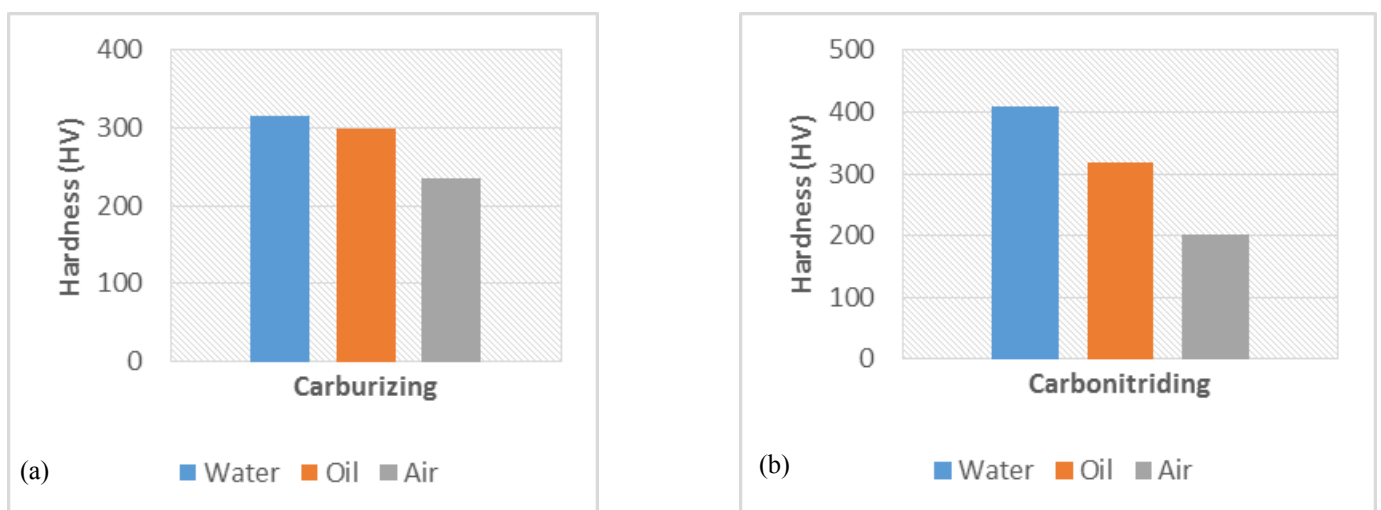
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	254746.6	6	42457.77	106.8015	5.63E-18	2.445259
Within Groups	11131.09	28	397.539			
Total	265877.7	34				

Table 5 Analysis of variance of Surface hardness

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	14083.39	6	2347.231	53.96908	4.21E-14	2.445259
Within Groups	1217.78	28	43.49214			
Total	15301.17	34				

**Figure 4** Boxplot of tensile strength means of the various treatments**Table 6** Analysis of variance of tensile strength

Source of Variation	SS	DF	MS	F	P-value	F crit
Between Groups	547.3257	6	91.22095	4.953814	0.00645	2.847726
Within Groups	257.8	14	18.41429			
Total	805.1257	20				

**Figure 5** Effect of quenchant on hardness in (a) carburizing and (b) carbonitriding

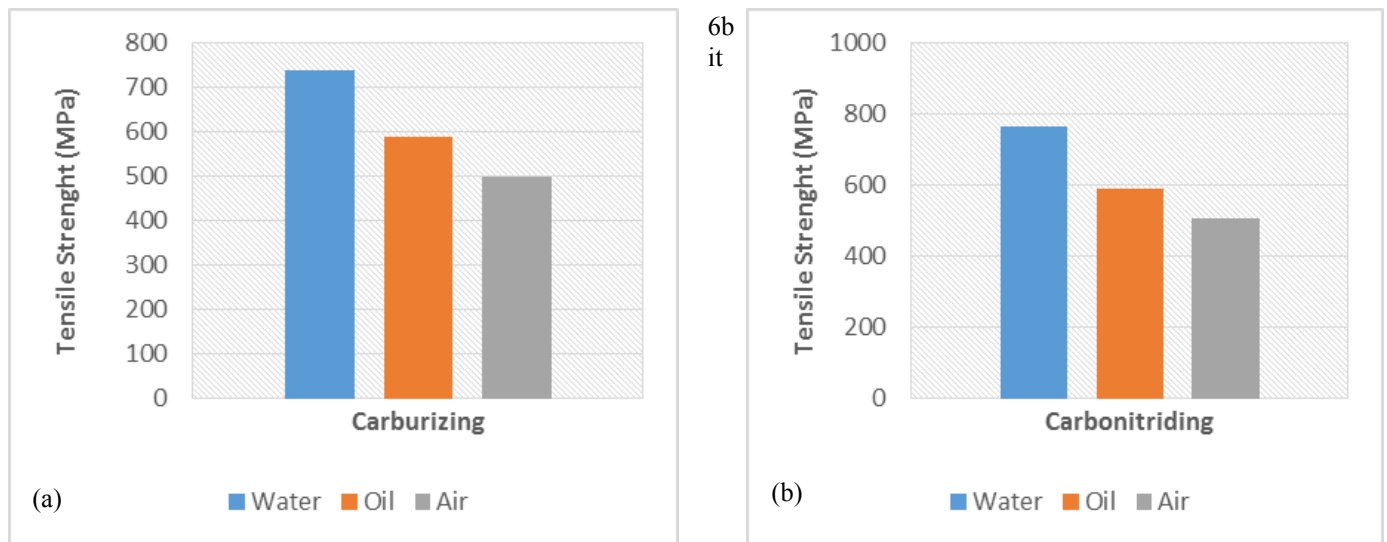


Figure 6 Effect quenchant on tensile strength in carburizing (a) carburizing and (b) carbonitriding

Analysis of variance of the results revealed p-values of $5.63E-18$ and $4.21E-14$ for the core and surface hardness respectively. The p-values are less than 0.05 which indicates that there exists a statistically significant difference between the treatments considered for the study. This suggests that carbonitriding and water quenching treatment gives the best output among the treatments applied.

Effect of surface treatment on tensile strength

Under the tensile strength analysis, specimen treated under T4 (carbonitriding with water quenching) recorded the highest tensile strength (767.79 MPa) while specimen treated under T3 (carburizing and air quenching) recorded the least tensile strength (500.89 MPa). This suggests that carbonitriding with water quenching treatment gives the best output while carburizing with air quenching produced the least improvement in tensile strength among the treatments. A graphical presentation of the results from the experimental data is shown in Figure 4.

The ANOVA results of variations between means of treatments for tensile strength is shown in Table 6. The ANOVA results on variations in the means of the treatments revealed a p-value of 0.00645 which indicates that statistically there is significant difference between the mean values obtained. This suggests that, all treatments combinations except quenching in air which yielded value lower than the control can be applied to improve the strength of hammers that are produced locally. However, T4 (carbonitriding with water quenching) yielded the highest among all treatments.

Effect of quenchant on hardness under carburizing and carbonitriding

Cooling rate has critical effect on the micro hardness of heat-treated steel. According to Calik (2009), hardness increases with increasing cooling rate and carbon content as a result of solid solution hardening and martensite formation. In comparing the effect of cooling rate of each quenchant on the surface hardening technique, it was observed that for each surface hardening technique applied, quenching in water yielded the highest surface hardness value followed by quenching in oil while quenching in air recorded the least hardness as shown in Figure 5.

Effect of quenchant on tensile strength under carburizing and carbonitriding

The effect of quenching medium on the tensile strength of treated hammers were analysed. As presented in Figure 6a and

was observed that quenching in water yielded the highest tensile strength of 741.02 MPa for specimen with surface treatment under carburizing and 767.78 MPa for specimen with under carbonitriding respectively. Quenching in air yielded the least tensile strength under both hardening techniques.

This phenomenon is attributed to the effect of the cooling rate of the quenching medium on the specimen. Among the three quenchants used, Dossett and Boyer, (2006) reports that water has the highest cooling rate, followed by oil and air in that order. In a similar study, Ahaneku et al. (2012), reported that, the specimen quenched with water after surface treatment yielded higher strength, hardness and toughness compared to other specimens that were quenched in air, furnace and oil. This corroborates the trend observed in this study in which water, the fastest cooling medium yielded the highest surface hardness and tensile strength values in each surface treatment technique. Quenching in air yielded the least surface hardness and tensile strength in both hardening techniques due to the slow cooling effect of air. This implies that, in either of the surface hardening techniques applied, the higher the cooling rate of quenchant, the higher the tensile strength and vice versa.

Conclusion

Carburizing and carbonitriding case-hardening techniques have been applied under water, air and oil quenching media to improve the hardness and tensile strength of locally produced hammermill hammers. The results indicate that all the six treatment combinations yielded an increased hardness of the steel which is a critical factor that affects the wear rate of the material during feed production. The surface hardening treatment by carbonitriding yielded the best results in improving the selected properties of the hammers.

The study showed that case-hardening using carbonitriding with NPK (30:10:10) fertilizer as a nitrogen source and water quenching yielded the highest surface hardness and tensile strength of 410.06 HV and 768.79 MPa, respectively, representing about a 218 % increase in hardness and a 47 % increase in tensile strength compared to the values of the control (untreated hammer) sample, which were 128.92 HV and 522.41 MPa, respectively. The case-hardened hammer can provide high resistance to wear due to its improved hardness. It is recommended that local manufacturers of feed mills and producers of hammers should consider using the current treatment process to produce hammers for feed processing in Ghana while further research focus on using other cheaper source of nitrogen such as urea.

Acknowledgement

The authors acknowledge the funding support received from USDA FAS Food for Progress to undertake this research.

Conflict of Interest Declarations

The researchers declare no conflict of interest.

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