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RESEARCH PAPER

Comparative analysis of pack carburizing, flame hardening, and quenching techniques used for surface hardening of AISI 1020 steel

Avaneesh Rajesh Kulkarni[1], Tejas Kukreja[1], Saurabh Dewangan[1]*

[1]Department of Mechanical Engineering, Manipal University Jaipur, Jaipur, Rajasthan, India, Pin-303007

*Corresponding author: saurabh.dewangan@jaipur.manipal.edu, tel.: 0141-3999100-838, Department of Mechanical Engineering, Manipal University Jaipur, Jaipur, Rajasthan, India, Pin-303007

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ABSTRACT

AISI 1020 steel is widely utilized in various fabrication processes, construction works, and automobile assemblies. Sometimes, hardness and toughness become very important for different machine parts. The surface hardening techniques, like pack carburizing and flame hardening, are two important approaches to enhance the hardness of the low-carbon steel while maintaining a good amount of toughness. In the present work, a comparative analysis has been carried out among pack carburizing, flame hardening, and quenching methods done on AISI 1020 steel. The analysis has been made based on hardness, toughness, and microstructural characterization. The quenching phenomenon is a different approach from surface hardening. The microstructural changes occur throughout the sample during the quenching process. Standard-shaped AISI 1020 steel samples were subjected to air quenching, pack carburizing, and flame hardening. The microstructural and phase changes were analysed using optical microscopy and X-ray diffraction (XRD) analysis. In addition, the Rockwell hardness (B scale) test and Charpy impact test were conducted to check the steel's variation in hardness and toughness after heat treatment. According to the analysis, the as-received sample exhibits an excellent mix of hardness and toughness, with a toughness of 209.25 J that rises to 268 J following water quenching. With a hardness of 225.5 J, the pack carburized sample outperforms the as-received sample by 8%. Additionally, the flame-hardened sample exhibits a reasonable balance between surface hardness and toughness.

Keywords: AISI 1020; Pack carburizing; Flame hardening; Quenching; Hardness; Toughness; Microscopy; XRD

INTRODUCTION

The surface hardening technique increases the wear resistance of components such as turbines, cam gears, bearings, and automobile parts. It lessens the onset and spread of cracks by offering a firm surface and impact resistance. Because surface hardening may be applied to less costly low-carbon and medium-carbon steels with less deformation and breaking, it is preferable to use through hardening [1, 2]. *Pack carburizing* is one of the case-hardening techniques which involves enriching low-carbon steels with carbon derived from a solid compound. Barium carbonate, calcium carbonate, potassium carbonate, sodium carbonate, and other energizers or activators that may be incorporated in the carburizing substance improve the diffusion of carbon atoms. One of the crucial factors in carburized steels is the analysis of case depth or hardenability. A cross section of carburized specimens is subjected to microhardness testing to ascertain case depth. Pack carburising is often used for low-carbon and low-alloy steel alloys. Samples produced by this method have both high core toughness and high surface hardness [3, 4, 5]. *Flame hardening* is a heat treatment technique that creates a hard martensite coating over a softer internal core by directly applying oxyfuel gas flames to the steel, especially gears made of steel. The two forms of flame hardening processes for the gears are tooth-at-a-time and spin hardening. Gears with sufficient bulk to absorb excessive heat without distorting are ideally suited for spin hardening. While the tooth-at-a-time approach merely hardens the flank, the tooth-to-tooth process employs the machine to heat and quench the gear [6]. The term *quenching* describes the rapid cooling of a heated steel, to change its crystal structure from austenite to possibly martensite or bainite, greatly increasing its hardness and strength by effectively "trapping" carbon atoms within the lattice. This is accomplished by immersing the hot metal at a controlled rate in a cooling medium, such as water or oil, which stops the carbon atoms from rearranging into a softer phase and causes martensite to form [7].

Low carbon steels like AISI 1020 are known for their good toughness, strength, and ductility, making them suitable for producing motor parts like axles, valves, cams, rockers, shafts, pinions, racks, and gears [8-11]. Low-carbon steels, however, are less hard and have worse mechanical strength than high-carbon steel. As a result, surface treatment is frequently used in practical applications to guarantee that the components meet the required performance criteria. Conventional heat-treatment techniques do not significantly increase the strength and hardness of low-carbon steel components. As a result, case carburizing, immersion hardening, cold-working, and induction hardening are typically chosen [12-14]. Among these techniques, case carburizing is one of the most popular since it works very well. To encourage the diffusion of carbon atoms into the component surface, the components are heated above a specific critical value while enclosed in a carbon powder box during the pack carburization process. After that, the carburised part is either taken out of the furnace and quenched with water or allowed to cool naturally in the furnace. The final product retains the inherent toughness and ductility of the original material in the core while having an exceptionally high surface hardness [15-17]. Crucially, the time and temperature of the carburizing process may be adjusted to affect the component's material properties. Higher temperatures and longer carburizing durations provide a thicker carbon diffusion layer, increasing surface hardness. Charcoal, sodium carbonate ($NaCO_3$), and barium carbonate ($BaCO_3$) are some of the carbon sources that can be used in the pack carburizing process [18-23]. Because of their improved stiffness/density ratio, high modulus steels hold promises for lightweight design solutions. This work investigates how the microstructure and mechanical characteristics of high modulus steels based on $Fe\text{-}TiB_2$ and $Fe\text{-}Cr\text{-}M_2B$ are affected by low-pressure carburizing and plasma nitriding. While carburizing produces a slightly lower maximum hardness value, nitriding produces enlarged ferrite. The paper discusses improving alloy ideas and thermochemical processing parameters for high modulus steels and the consequences for engineering applications [24]. The carburization of mild steel, an alloy that is essential for engineering applications because of its low cost and good tensile strength, is examined in this paper. It looks into several carburization techniques, quality-affecting variables, and the possibility of organic additives for carburizing low-carbon steel. The advantages of organic energizers are also included in the paper, along with recommendations for further study on mild steel carburization using organic additives [25]. A study investigates the effects of steel composition, carburizing time, and energizer materials on the mechanical characteristics and case depth of low-carbon steel. It determines the ideal energizer material by numerical processes. In addition, the study compares pack carburizing methods and looks at boundary conditions, microstructure, and hardenability curves [26]. The effect of pack carburizing on the fatigue behavior of a notched beam with a depth of 1 mm and an angle of 45° is examined in this work. Fatigue testing, heat treatments, and mechanical tests were all part of the study. The Fatigue Life Improvement Factor rose by 8.20%, 14.3%, and 15.9%, respectively, indicating that soaking time improved fatigue strength and lifetime

[27]. The process of heating and cooling metal to provide the required mechanical properties is known as heat treatment. It offers case hardening, vacuum hardening, low-pressure carburization, nitriding, tempering, and brazing. According to a study on traditional case hardening, human labor required 244.98 minutes [28]. Darmo et al. used teak wood charcoal and powdered Pomacea Canalikulata Lamarck shell for pack carburization of SS400 steel cylinders, demonstrating that PCL shell power significantly increased the components' hardness [29]. Additionally, Soenoko et al. [30] employed PCL shell powder to stimulate the carburization of SS400 steel components. They discovered that tempering and quenching the carburized parts in 30% NaCl solution might improve the final components' fatigue strength. The impact resistance and stiffness of carburized mild steel specimens were both enhanced by the inclusion of ground bone as an energizer, according to Aramide et al. [31]. Low carbon steel was pack carburized by Negara and Widiyarta [32] using either bamboo charcoal (BC) or goat bone charcoal (GBC) as the carburizing medium. The findings demonstrated that, with the right carburizer selection (i.e., GBC or BC), a notable increase in hardness, tensile strength, yield strength, and elastic modulus could be achieved. Ramli et al. (2021) explored using coconut and dog conch shell powder as carburizing media for SCM 420 steel pack carburization. Results showed that a 60% content of coconut shell and 40% content of dog conch with extended carburizing time increased carbon content and surface hardness and increased carburized layer thickness [33].

In the automobile transmission system, transmissions are crucial components that impact the dependability and performance of the vehicle. They transfer rotational speed and power, and efficiency is impacted by accuracy. Because heavy-duty transmissions operate in challenging conditions, they need gears that are robust, impact-resistant, and wear-resistant. Treatments like quenching and carburizing are applied to enhance mechanical qualities. Heat treatment, however, can cause gear deformation, impacting fatigue life, precision, trial production, transmission efficiency, vibration, and noise. As a result, it's imperative to ensure gears have exceptional performance qualities [34, 35]. A multi-field model for carburizing quenching that takes into account the distortion of interstitial solid solution brought on by carburization is presented in this work. Using Dante heat treatment software and testing on cylindrical samples, the correctness of the model was confirmed. A finite element model was also built to anticipate gear deformation, considering dynamic heat boundary conditions and flow effects. Compared to traditional models, the model showed improved prediction accuracy in torsional and expansion deformation, offering a new way to forecast carburizing and quenching deformation in gears [36].

In the direction of low carbon steel surface hardening, the present work deals with a comparative assessment of three hardening techniques i.e.: pack carburizing, flame hardening, and water quenching. The hardness, toughness and microstructural orientation were analysed on the samples, and the characteristics of heat-treated AISI 1020 steel samples were compared with those of the ‘as received’ sample. A considerable change in the mechanical properties was reported in this work, which was further established by the optical microscopy and XRD analysis.

MATERIALS AND METHODOLOGY

A square-shaped cross-sectional rod of AISI 1020 steel was collected from an ISO certified industry. This steel was in hot rolled condition. From this rod, 16 samples were cut in the standard size provided by ASTM E23. The specimen’s length was 55 mm, with its cross section of 10 ×10 mm^2. A ‘V’ notch was cut at the mid-length of the specimens (**Fig. 1**). First four specimens were considered in ‘as received’ or original condition. Next four samples were heated in an induction furnace for 2 hours at a soaking temperature of 800°C. After attaining required temperature and time, these samples were quenched in water. Another four sets of samples were put inside a metallurgical chamber filled with powdered coal. The average grain size of the coal was 2-3 mm. The coal was properly compacted, and all the sides of the chamber were sealed. The closed chamber was then kept in induction furnace for heating at a high temperature of 900°C for a soaking period of 5 hours. Another four set of samples were kept on an anvil and heated collectively by using flame produced by butane gas. The samples were chilled by water followed by flame heating time of 2 min.

The heat-treated specimens were tested under Charpy impact test and Rockwell hardness test. An average toughness value was measured by taking the results of four different specimens. For conducting hardness test, three indentations were made on each sample, and the average hardness was considered for that sample. The microstructural changes in the samples were observed by using optical microscopy. A thorough polishing was conducted on the desired surface of the samples. The ‘as received’ and water quenched specimens were polished on their outer surface only whereas the pack carburized and flame hardened samples were polished on their two surfaces, the outer surface and the core region. The polishing was performed using five different grades of abrasive papers of grit sizes- 500, 1000, 1500, 2200, and 2800. The cylindrical grinder of make “Chennai Metco” was used to rotate abrasive papers. The polished surfaces were etched by using 3% Nital etchant before microscopy. The microstructural images were captured at two different magnifications of 200X and 500X for proper understanding of structural changes. In addition, the XRD analysis was also conducted to check various phases on the surface of the samples. No surface preparation was done to conduct XRD. It was performed on ‘as heat treated’ condition of the samples.

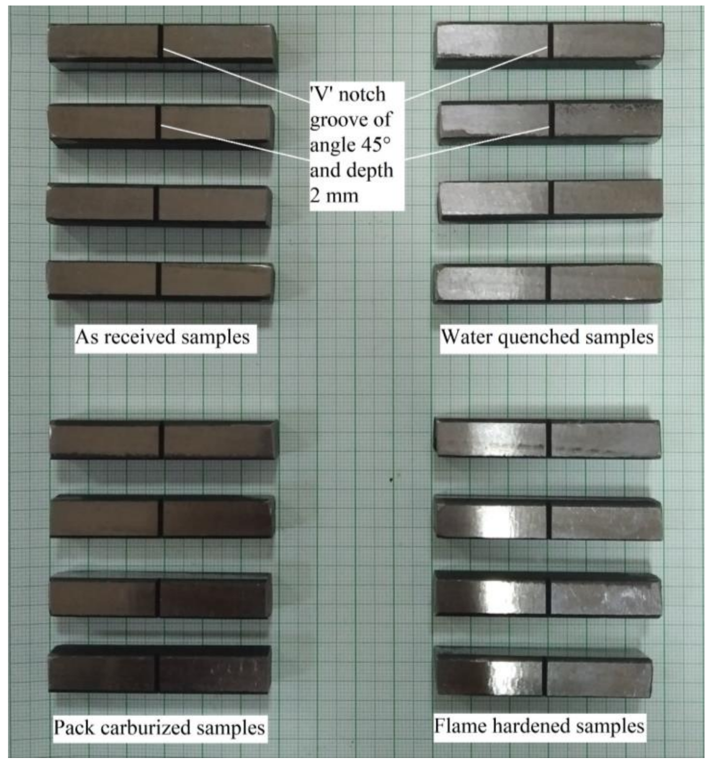


Fig. 1 AISI 1020 samples used in this work

RESULT ANALYSIS

Microstructural analysis: The microstructural analysis of ‘as received’ sample was done to check the orientation of ferrite, pearlite, and other possible phases. The microstructure of hardened samples has been analysed based on the results of the ‘as received’ sample. **Fig. 2** shows the microstructure of as received sample. The ‘as received’ sample showed bright ferrite content in the fine and compacted pearlite phase. No lamella between α and Fe_3C was noted in this sample. Bainite has been reported over the ferrite grains in the form of dark particles and pin shape. Bainite was generally reported as sheaves over the ferrite grains. According to [37, 38, 39], bainite nucleates at the austenite grain boundary. Because of this, the hardness of the steel increases.

The microstructure of water quenched sample is shown in **Fig. 3**. At low magnification of 200X, the black colored zones, i.e., pearlites are lesser than those reported in ‘as received’ sample. The pearlite growth has been arrested by quenching the sample into water. The available pearlite is very fine, and no lamella has been seen between ferrite and cementite. The ferrite has two distinct appearance- fairly bright grains and grains with multiple dots. The bright grains are showing pure ferrite with no or negligible formation of bainite over there while the second type of ferrite grains are carrying an aggregate bainite phase as numerous black dots. The bainite formation has increased in the water quenched samples as compared to that of ‘as received’ sample.

(a)

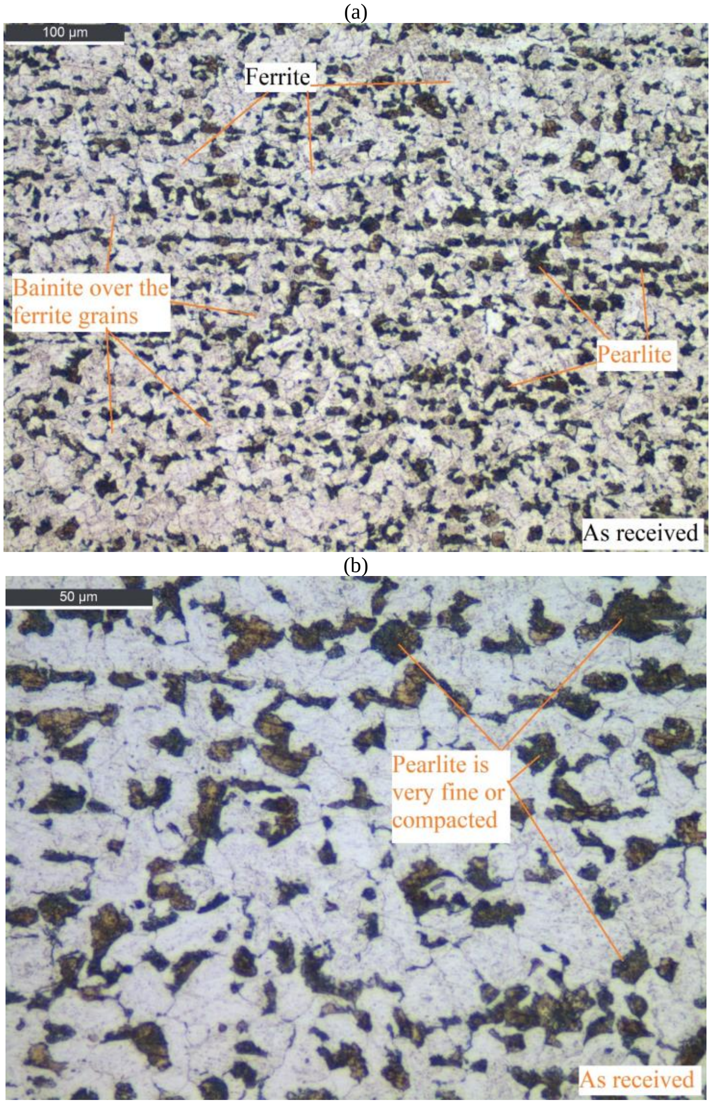


Fig. 2 Microstructure of ‘as received’ sample: (a) at 200X magnification; (b) at 500X magnification

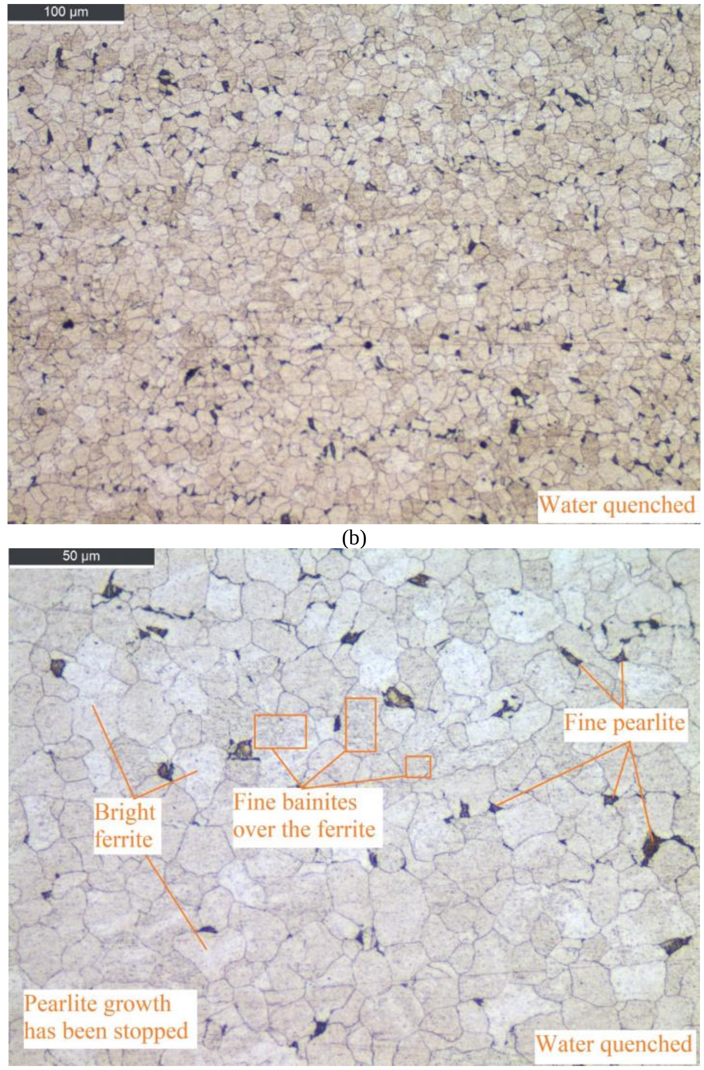
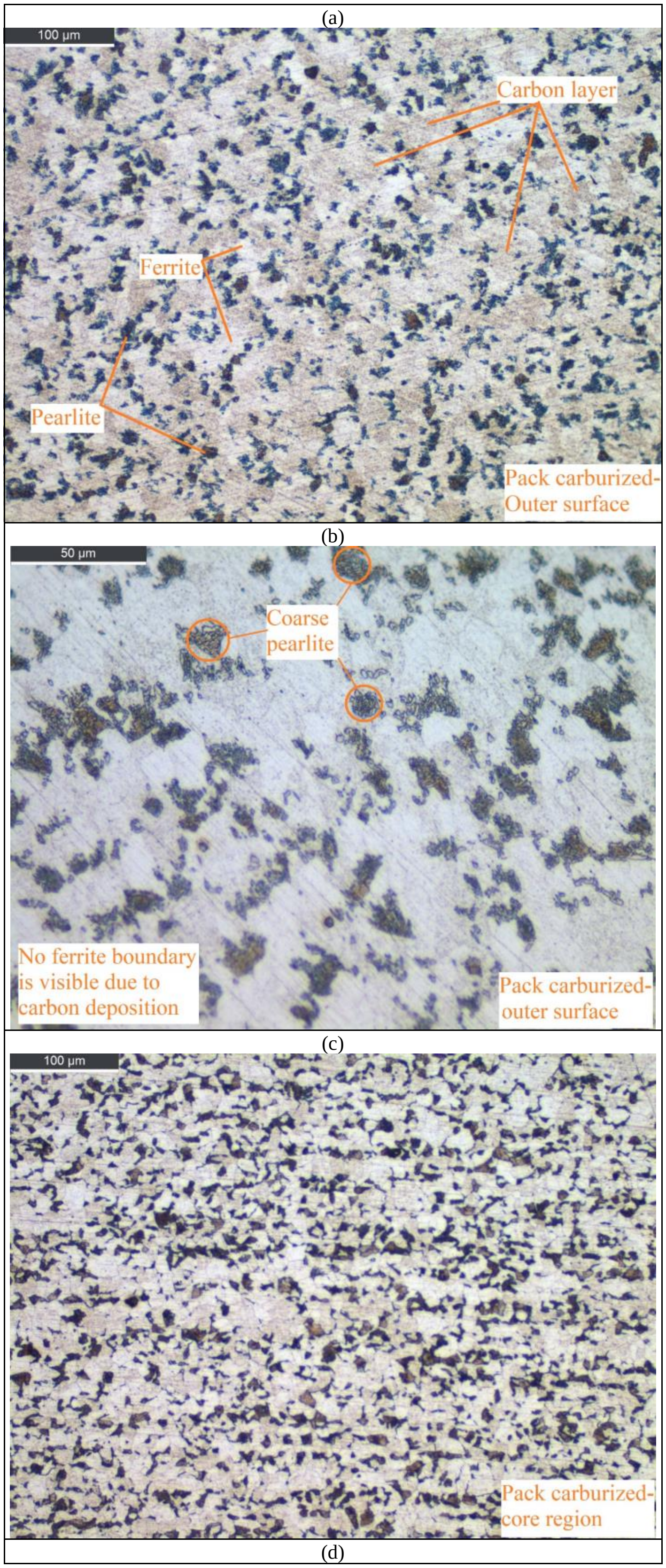


Fig. 3 Microstructure of ‘water quenched’ sample: (a) at 200X magnification; (b) at 500X magnification

The pack carburized sample has been analysed on its two sides- first, at the outer surface directly exposed to the heated carbon powder, and second, the core region of the sample. The microstructure of the pack carburised sample's outer surface shows visible changes compared to that of the ‘as received’ sample. At low magnification of 200x, the ferrite grains are showing brown coloured layer which is establishing the presence of carbon layer that is deposited due to the high temperature exposure of metallic chamber. Due to the presence of carbon layer, the ferrite grain boundary is not visible in this sample (Fig. 4b), although the layer thickness could not be measured in this work. The microstructure at the core region of this sample is shown in **Fig. 4 (c, d)**. The structure at the core region is similar to that of ‘as received’ sample. The ferrite can be seen with its grain boundary. Also, like ‘as received’ sample, the pearlite is compacted at the core of the sample. Hence, pack carburizing has not affected the central part of the sample.

(a)



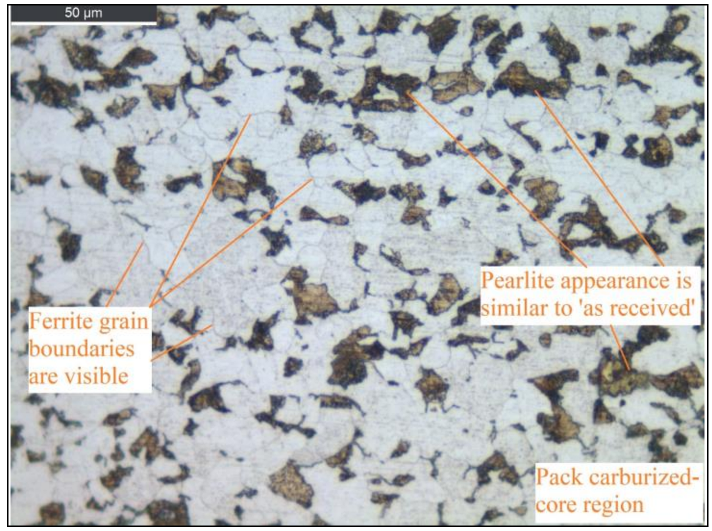
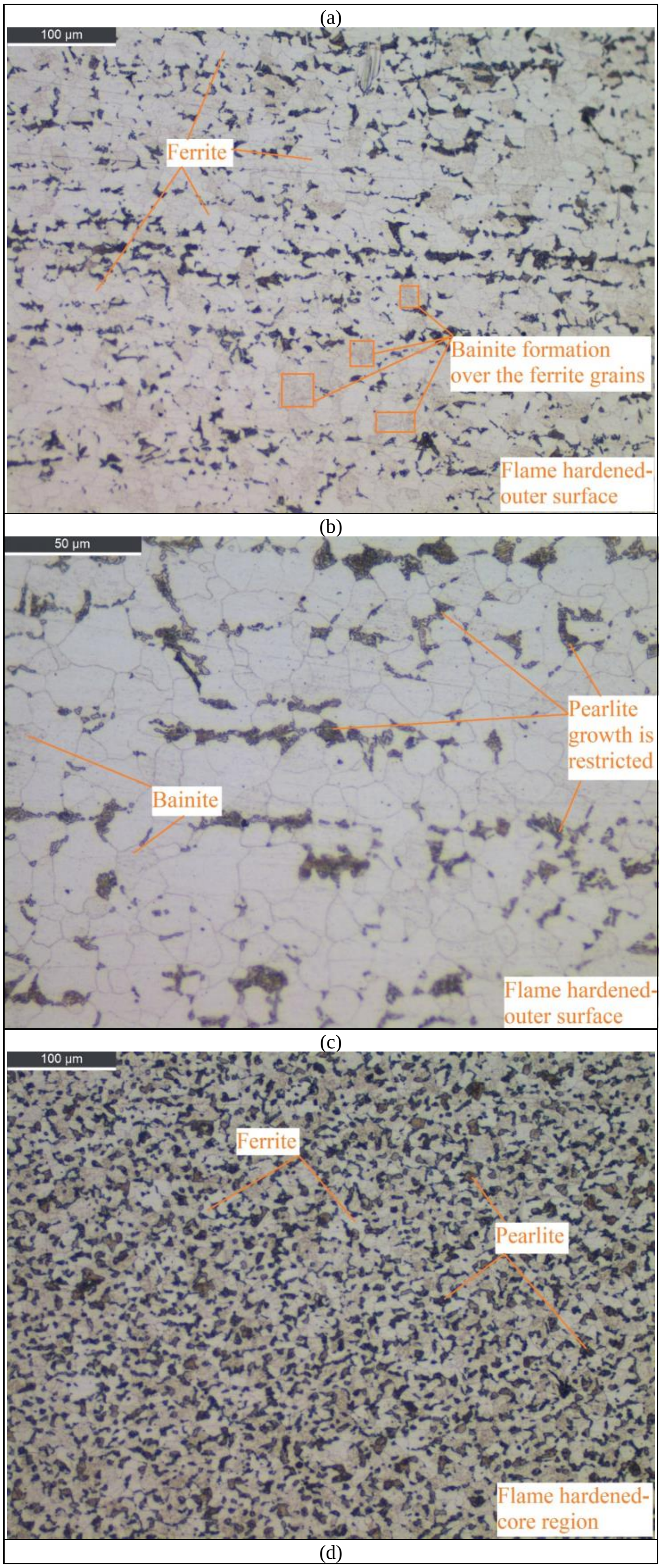


Fig. 4 Microstructure of pack carburized sample: (a) Image captured at 200X magnification on the outer surface; (b) Image captured at 500X magnification on the outer surface; (c) Image captured at 200X magnification on the core region; (d) Image captured at 500X magnification on the core region

The flame-hardened sample has also been analysed on two different surfaces- the outer surface and the core surface. The effect of flame heating and quenching on the microstructure of the outer surface is shown in **Fig. 5 (a, b)**. The image with 200x magnification shows very fine and compacted pearlite as discussed in the case of the ‘water quenched’ sample. Also, the ferrite has two appearances- fairly bright and bainitic ferrite. The complete structure of the outer surface of the flame-hardened sample is the same as that of the water-quenched one. The growth of pearlite has been restricted by the sudden sprinkling of water over the flame-heated surface. Compared to the surface, the core region of the same sample’s microstructure is completely different (**Fig. 5 c, d**). Ferrite and pearlite are nearly equal in the core region. Also, the pearlite is coarse and compacted in this sample, the same as reported in the ‘as received’ sample. Hence, the flame hardening phenomenon has not affected the properties of the core region of the steel.

Hardness analysis: Three indentations were made on each sample to get a favourable hardness value. Since four samples were considered in each category of physical condition, there were 12 hardness readings for each category. The different values of hardness for various samples are shown in **Table 1**. The ‘as received’ sample has an average hardness of 97 HRB, increasing to 105.6 HRB after water quenching. The pack carburised sample possesses a hardness of 91.2 HRB, which is lower than that of the ‘as received’ sample. Since the as-received sample was hot rolled, its microstructure is slightly compacted. During heating process of pack carburizing, the microstructure gets equiaxed and hence the hardness of the same is slightly lower than the as received sample. After flame heating + quenching, the sample’s hardness gets improved to 100 HRB which is nearly 3% higher than the received sample. A comparative bar chart of hardness values of different samples is shown in **Fig. 6**.



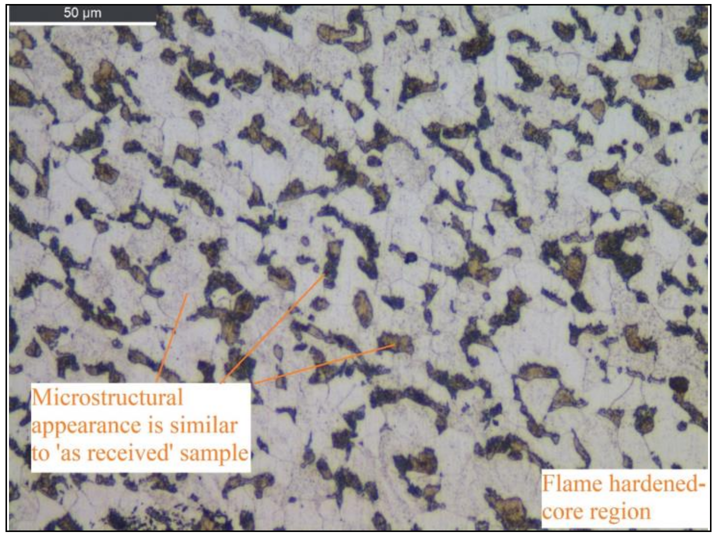


Fig. 5 Microstructure of flame hardened sample: (a) Image captured at 200X magnification on the outer surface; (b) Image captured at 500X magnification on the outer surface; (c) Image captured at 200X magnification on the core region; (d) Image captured at 500X magnification on the core region

Table 1 Hardness measurement at different locations of different samples

Sample	Physical condition	Test-1 (HRB)	Test-2 (HRB)	Test-3 (HRB)	Average hardness (HRB)
1-a	As received	94	97	97	97
1-b		98	100	98	
1-c		95	93	94	
1-d		97	100	100	
2-a	Water quenched	100	105	95	105.6
2-b		108	114	105	
2-c		107	113	109	
2-d		104	101	106	
3-a	Pack carburized	90	92	92	91.2
3-b		88	92	94	
3-c		92	88	89	
3-d		87	96	94	
4-a	Flame hardened	95	96	98	100
4-b		104	105	103	
4-c		103	97	99	
4-d		104	105	96	

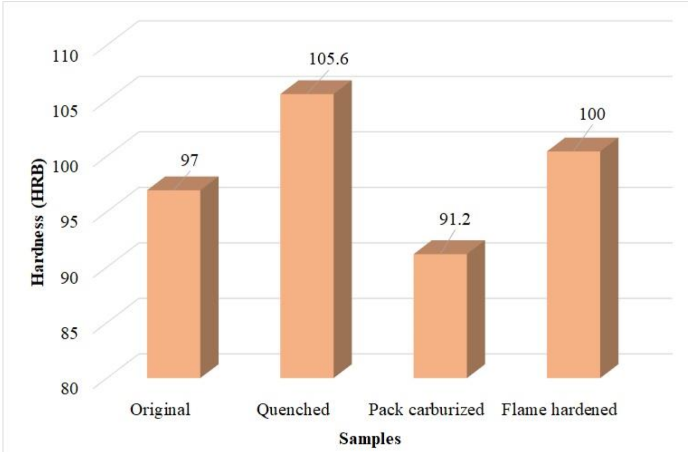


Fig. 6 Comparative analysis of hardness in four different physical conditions of AISI 1020

Toughness analysis: The toughness of the samples used in the study is given in **Table 2**. As four samples were in each physical condition, an average toughness (J) value was measured for each category. The 'as received' sample showed a toughness of 209.25 J, drastically increasing to 268 J after water quenching with nearly a 28% increment. In this study, the water-quenched sample contains no martensitic structure; only bainites have been reported. Therefore, a good combination of hardness and toughness was reported in the quenched sample. The pack carburised sample carries a toughness of 225.5 J, 8% higher than the as-received sample. The pack carburizing process has increased both hardness and toughness. The high heat application has made the microstructure equiaxed, stress-free and tougher than the as-received sample. The flame hardened sample has also shown a good improvement in the toughness value i.e., 229.5 J. The flame hardening has converted the outer surface microstructure into fine pearlite and bainite, whereas the core region of the sample is an equiaxed microstructure. Therefore, a good combination of toughness and surface hardness was also noted in the flame-hardened sample. A toughness comparison has been shown in the bar chart (**Fig. 7**).

Table 2 Toughness values of four different specimens

Sample	Test-1 (J)	Test-2 (J)	Test-3 (J)	Test-4 (J)	Average Value (J)
As received	210	210	209	208	209.25
Quenched	256	274	270	272	268
Pack carburized	220	240	222	220	225.5
Flame hardened	222	230	230	236	229.5

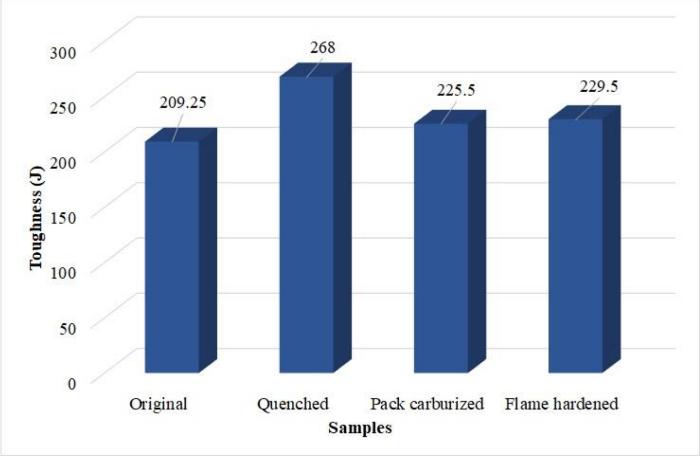


Fig. 7 Comparison of toughness in four samples under study

XRD analysis: The XRD analysis was done to observe the phases and compounds on the samples' surface. The XRD peaks of the samples are shown in **Fig. 8**.

The XRD peaks were identified using the results in [40-42]. The 'as received' sample has only two major peaks of α-Fe at 2θ of 44.5° and 65°. The quenched and flame-hardened samples have not shown the α-Fe because the XRD analysis was conducted directly on the heat-treated surface, and no surface preparation was done before the XRD test. Therefore, these two samples have shown all the peaks of iron oxides at various planes on 220, 311, 400, 511, 214, and 440 [43, 44]. The surface of the pack carburised sample, without polishing, possesses various iron oxide peaks in the planes of 220, 311, 400, 511, and 440. The α-Fe was recorded at 2θ of 44.5° and 65°. The deposition of carbon and other external elements was seen in this sample. The rock materials like quartz (2θ of 24° and 26°) and mullite (2θ of 33°, 49°, and 54°) were observed at the surface of pack carburized sample [45]. It establishes that a layer has been deposited after the pack carburizing process.

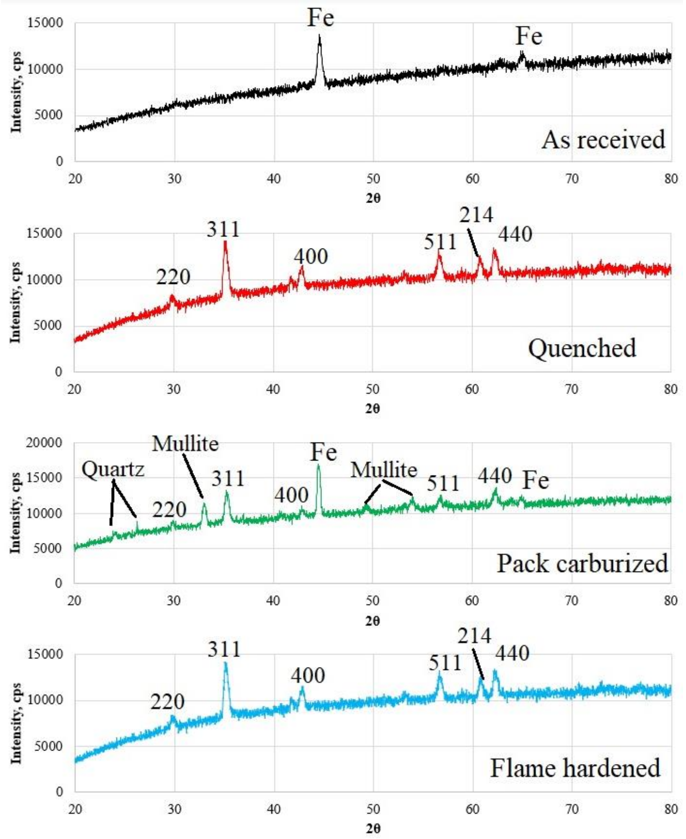


Fig. 8 XRD analysis on 'as received', quenched, pack carburized and flame hardened samples

CONCLUSION

Heat treatment, especially selective hardening treatments like pack carburizing, is widely used in industry to enhance the surface hardness and wear resistance of low-carbon steel components, particularly in applications like gears, shafts, and knives.

An attempt has been made to compare the effect of quenching, pack carburizing and flame hardening on the hardness, toughness, and microstructural characteristics of AISI 1020 steel. The as-received sample has been taken as the reference sample in this study. The following conclusion can be made from this study:

- The basic microstructural orientation such as ferrite, pearlite and some bainites observed in as received sample has altered after following pack carburizing, flame hardening and quenching methods.
- The quenching process adopted in this study has mainly developed the bainite but not martensite. Also, the pearlite has grown in a small amount. Therefore, the hardness and toughness both increased drastically in the quenched sample.
- The topography of the outer surface of the flame hardened sample is similar to that of the quenched sample, although the microstructural appearance of the core is like that of an 'as received' sample containing an equiaxed ferrite and pearlite.
- The pack carburized sample's outer layer shows a carbon layer deposited, which has increased the steel's hardness, although there is no effect on the microstructural appearance of the core region.
- The high heat application during the three heat treatment methods has equated the ferrite and pearlite. Therefore, the toughness of these samples has got significantly increased along with the hardness.

The present work has two limitations: (1) Absence of martensite after quenching; (2) Reduced hardness of pack carburized sample than 'as-received' sample.

It is sometimes possible for martensite not to form after quenching, especially in low-carbon steels when cooling rates are insufficient or interrupted. The present

work involves small samples that came into contact with air during removal from the furnace and dipping into water. This resulted in the formation of other phases, like pearlite and bainite, but not martensite.
The low hardness of the pack carburized sample can be due to short carburizing time, low carburizing temperature, and inadequate carbon grain size. The pack carburizing process can be enhanced by using various sizes of carbon powder (up to the micro level of grain size), varying heating temperature, and different heat soaking time. Hence, continuous research is always needed to achieve the best results.

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