

CARBURIZATION AND CHARACTERIZATION OF HIGH-SPEED STEEL SINGLE-POINT CUTTING TOOLS USING WALNUT SHELL AS A CARBURIZING AGENT

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ABSTRACT

This research investigated the carburization and characterization of M2 grade high speed steel (HSS) single point cutting tools using walnut shell as a sustainable carbon source. Ten M2 HSS samples (10 mm × 10 mm × 40 mm) were carburized at 850 °C, 900 °C, and 950 °C for holding times of 30, 60, and 90 minutes, followed by oil quenching. Hardness was evaluated using the Rockwell A (HRA) scale, while microstructural and elemental changes were analyzed using SEM-EDS. The control sample exhibited a baseline hardness of 76.4 HRA. After carburization, there was a significant increase in surface hardness, with the highest value of 88.9 HRA achieved at 900 °C for 90 minutes, which it is the optimum treatment condition. At 850 °C, hardness ranged from 70.7 to 82.2 HRA, while carburizing at 950 °C produced hardness values between 78.0 and 87.8 HRA. SEM observations revealed progressive carbide formation, surface densification, and refined diffusion layers, particularly at higher temperatures and longer holding times. EDS analysis confirmed increased atomic surface carbon content, reaching up to 62.79 atomic percentage of carbon (at. % C) at intermediate diffusion stages and stabilizing between 12–35 at.% C after deeper diffusion and carbide formation. The study demonstrates that walnut shell provides sufficient carbon for effective pack carburization of M2 grade HSS, with 900 °C for 90 minutes producing the most uniform microstructure, strongest carbide dispersion, and highest hardness. These findings show that walnut shell can successfully enhance the surface properties of M2 grade HSS cutting tools, improving wear resistance and potential service performance.

Keywords: High-speed steel; Carburization; Walnut shell; Hardness; SEM; Sustainable materials.

1. | Introduction

The choice of suitable material for the tools is considered as one of the main factors for their durability and efficiency in the present manufacturing (M'saoubi *et al.*, 2008). The cutting tools made of high speed steel (HSS) are used widely in industry because of their combination of high hardness, high wear resistance, and high strength at high temperature (Pupan and Dolya, 2022). The properties make HSS

an indispensable material for high-performance machining processes where tool life and accuracy are crucial. However, with the increased industrial need for longer lasting tools, surface modification processes are needed to impart improved HSS attributes.

Carburizing is a thermochemical process, which is well established technique, that increases the carbon content on the surface of the steel to

increase the hardness, wear resistance and service life of the steel cutting tools (Adi and Malik, 2025). This results in a durable, tough surface and a tough core to resist fracture and absorb impact. The traditional carburization methods are based on synthetic carbonaceous materials; activated carbon (AC) and industrial powders (IP) (Al-Samarai and Al-Douri, 2024). These traditional agents are, however, expensive, non-renewable and environmentally unfriendly, thus, sustainable agents need to be developed (Ehi-Okoebor *et al.*, 2023).

In this regard, agricultural wastes like walnut shells have been identified to be the potential bio-based carburizing agents. The walnut shells are a rich and cheap food industry by-product with 17–49% fixed carbon (Sajdak *et al.*, 2022). Walnut shells are decomposed to gases like carbon monoxide (CO) under high-temperature conditions that facilitate carbon diffusion during the carburization process (Kieush *et al.*, 2022). Using walnut shells helps alleviate the use of artificial carbon, supports sustainable waste recycling, and is in line with principles of a circular economy (Edun *et al.*, 2024).

Although there has been a significant advancement in bio-based carburization research, using palm kernel shells, seashells, animal bones and other agricultural wastes by Oyetunji & Adeosun (2012), Afolalu *et al.* (2015) and others, the use of walnut shells for carburization of HSS cutting tools is under explored. To optimize the carburization process, a better knowledge of the influence of carburization conditions, such as temperature and holding time, in terms of hardness and microstructure is required.

This research is intended to investigate the effect of carburization temperature and holding time on the properties of the hardness and microstructural characteristic of M2 HSS cutting tools with walnut shell as the sustainable carburizing agent.

2. | Materials and Methods

A 3×3 full factorial design was used, with the two factors being carburizing temperature and holding time. The experiment was carried out on 10 samples of M2 grade HSS of dimension 10 mm x 10 mm x 40mm of which one was not carburized and remaining nine samples were carburized. The control sample was retained in the as received condition for comparison purposes. Each carburized sample was subjected to a unique temperature and time combination, followed by oil quenching after carburization. The response variables measured after treatment included hardness and microstructural characteristics. Rockwell hardness testing (HRA scale. model: HR-150A) was carried out at three different locations on each sample and the average was taken to determine the mechanical response of the carburized and control samples, while scanning electron microscopy coupled with energy dispersive spectroscopy (SEM–EDS) (thermos scientific phenomTM pharos desktop (SEMs) (resolution of 2.0nm to 20KV was used to evaluate the microstructure and elemental distribution)).

Nine samples of 10 mm x 10 mm x 40mm M2 HSS cutting tools were prepared, buried in prepared walnut shell granules, embedded in a 100 ml crucible and placed in a muffle furnace (model 5x-2.5-10 with a 1200 °C capacity) for carburization.

The temperature settings for this experiment were established at 850 °C, 900 °C, and 950 °C with each temperature settings used for carburization at 3 different holding time of 30 minutes, 60 minutes, and 90 minutes.

3. | Result

Rockwell hardness testing (HRA scale. model: HR-150A) was carried out at three different locations on

each sample and the average was taken to determine the hardness result shown in Table 1.

Table 1 | Rockwell hardness (HRA, 60kgf) result for each carburized sample

Temperature (°C)	30 minutes	60 minutes	90 minutes
control	76.4 HRA	76.4 HRA	76.4 HRA
850	70.7 HRA	82.2 HRA	81.8 HRA
900	76.4 HRA	82.7 HRA	88.9 HRA
950	78.0 HRA	84.9 HRA	87.8 HRA

Table 2 | SEM-EDS surface composition of carburized M2 HSS using walnut shell granules

Composition	Samples									
	Control	1	2	3	4	5	6	7	8	9
Fe (At %)	79.57	42.93	55.25	60.69	83.13	32.29	80.40	80.09	70.21	60.24
Fe (Wt %)	90.90	75.68	83.02	84.90	91.71	65.69	91.34	93.30	90.30	83.97
C (At%)	15.35	54.65	42.30	35.83	8.37	62.79	12.63	17.93	28.21	33.42
C (Wt %)	3.77	20.72	13.67	10.78	1.99	27.47	3.09	4.49	7.80	10.02
Cr (At %)	3.28	1.51	1.52	2.08	2.96	1.19	2.64	1.41	1.58	1.24
Cr (Wt %)	3.48	2.48	2.12	2.71	3.04	2.25	2.79	1.53	1.89	1.61
Mn (At %)	0.39	0.00	0.12	0.00	0.33	0.05	0.32	0.00	0.00	0.49
Mn (Wt %)	0.43	0.00	0.17	0.00	0.35	0.11	0.35	0.00	0.00	0.68
V (At %)	0.15	0.00	0.12	0.12	0.19	0.07	0.07	0.00	0.00	0.00
V (Wt %)	0.15	0.00	0.16	0.15	0.19	0.13	0.07	0.00	0.00	0.00
K (At %)	0.42	0.10	0.33	0.53	0.16	0.26	0.05	0.00	0.00	0.08
K (Wt %)	0.34	0.10	0.34	0.52	0.13	0.38	0.04	0.00	0.00	0.08

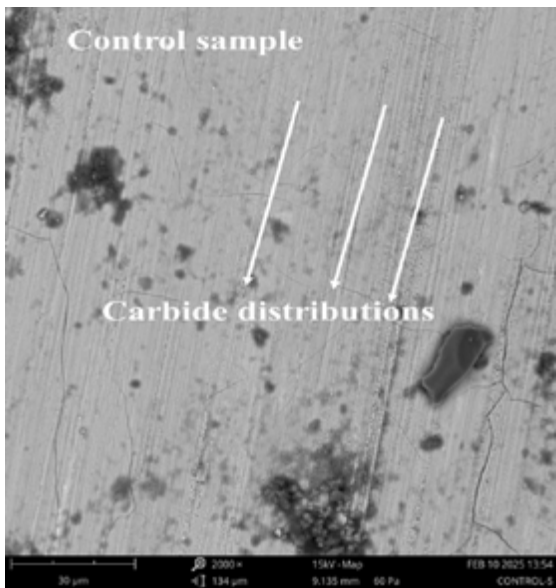


Figure 1 | Control sample microstructure

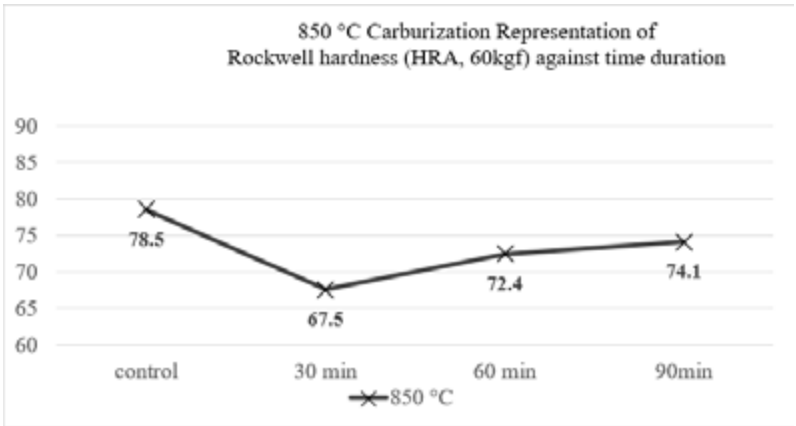


Figure 2 | Rockwell hardness graphical representation at 850 °C

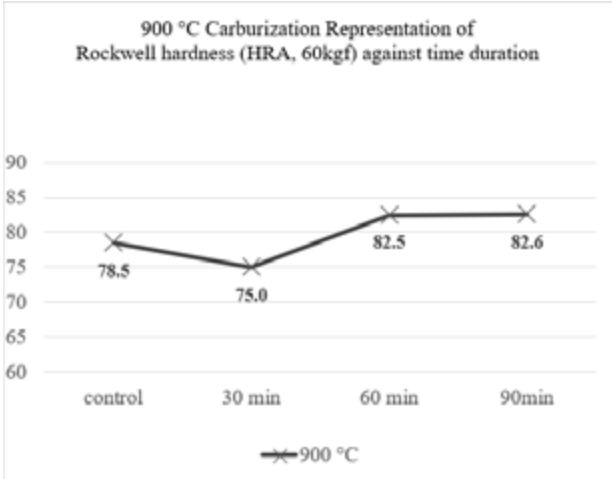


Figure 3 | Rockwell hardness graphical representation at 900 °C

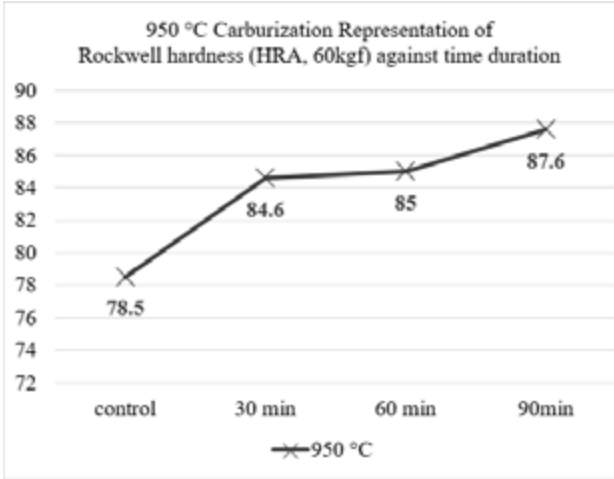


Figure 4 | Rockwell hardness graphical representation at 950 °C

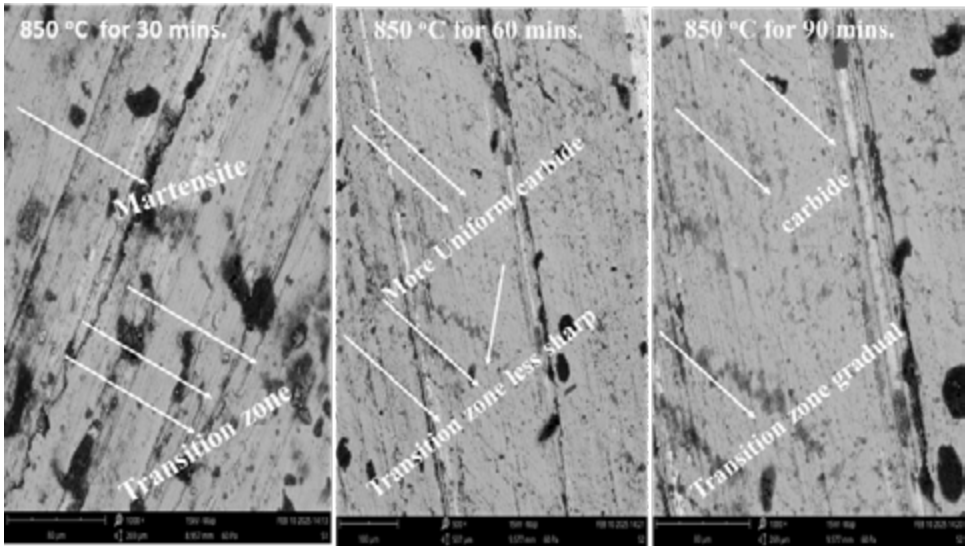


Figure 5 | Microstructural representation at 850 °C

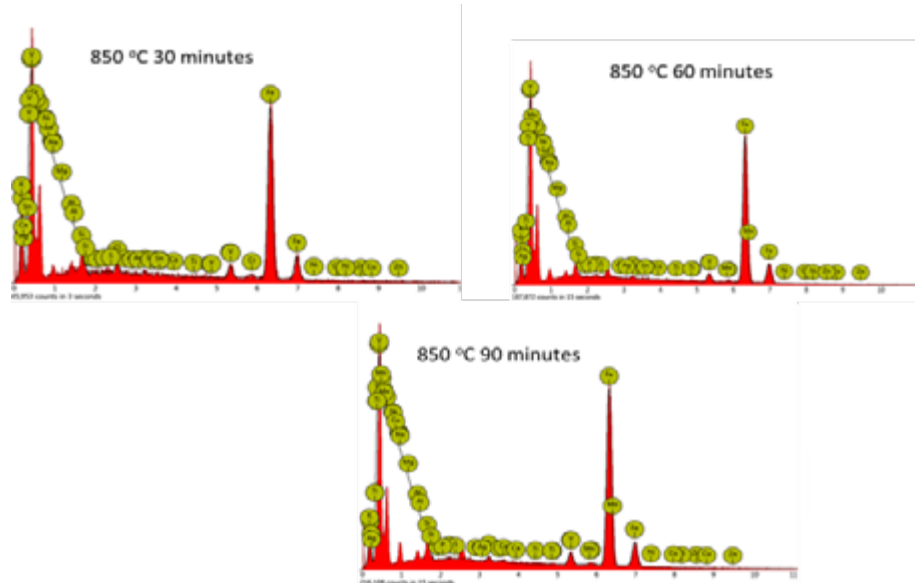


Figure 6 | EDS microstructural view at 850 °C

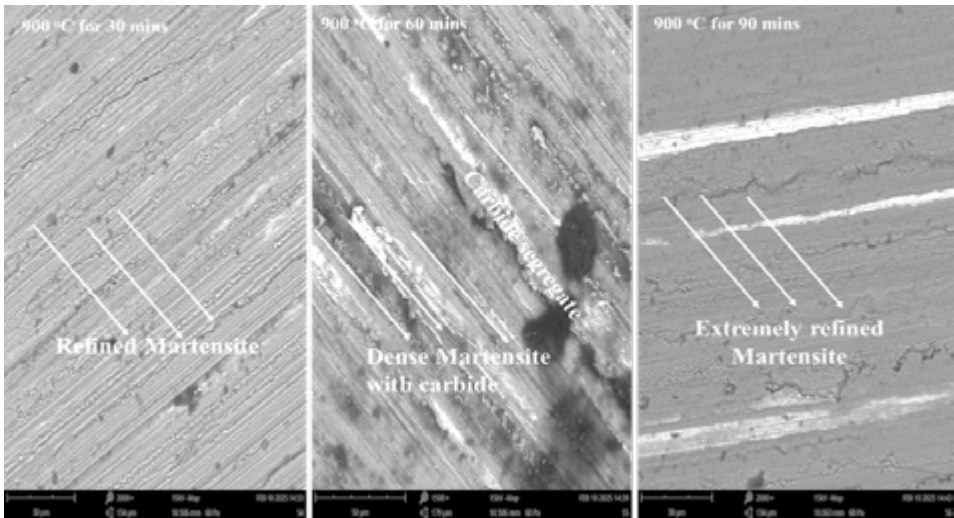


Figure 7 | Microstructural representation at 900 °C

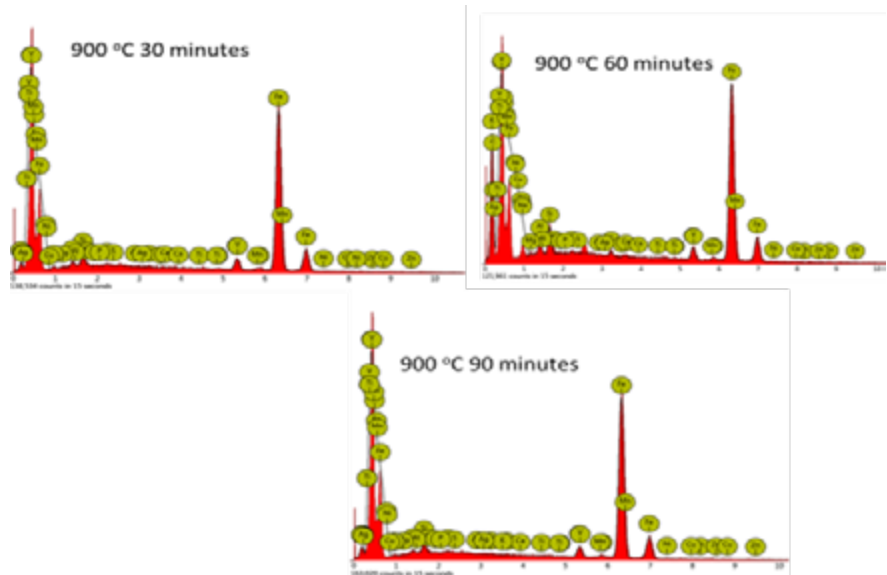


Figure 8 | EDS microstructural view at 900 °C

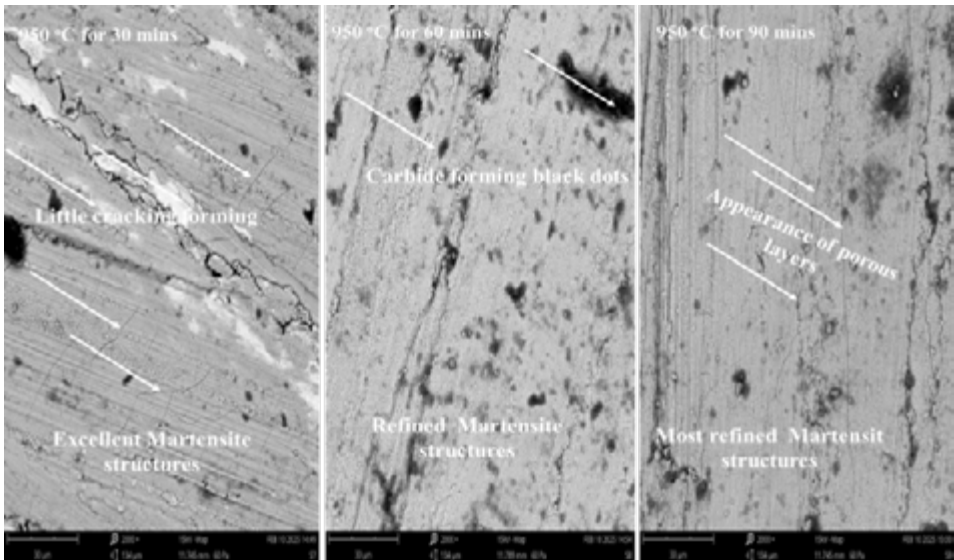


Figure 9 | Microstructural representation at 950 °C

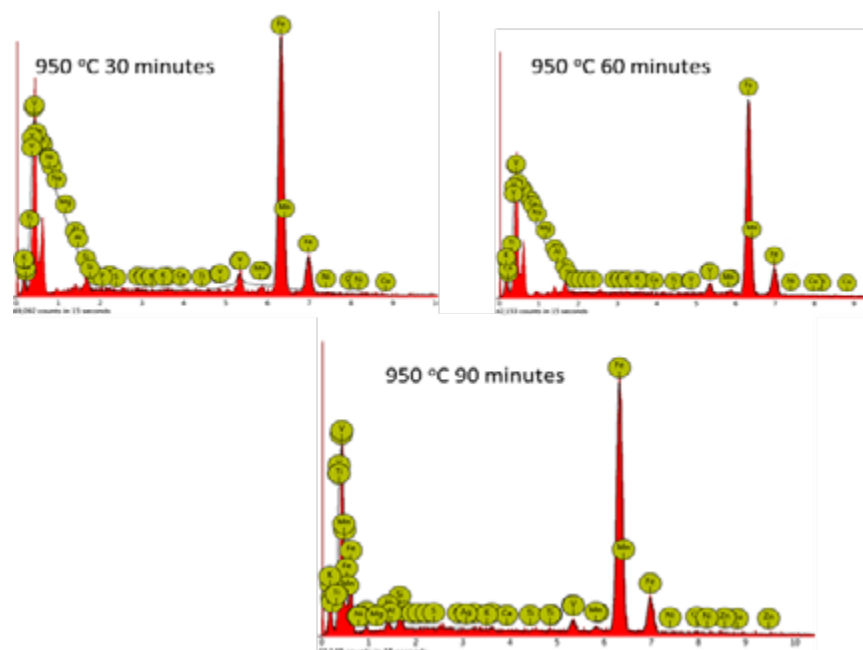


Figure 10 | EDS microstructural view at 950 °C

4. | Discussion

The results: Tables 1 and 2, and Figures 1-10 revealed a significant improvement in the hardness of M2 high-speed steel (HSS) cutting tools after carburization with walnut shell granules. Best hardness value of 87.6 HRA at 60 kgf load was achieved at the temperature of 950 °C and holding time of 90 min. while 78.5 HRA at 60 kgf load was obtained for the untreated control. This suggests that temperature and the duration of holding both increased with the carbon diffusion into the steel matrix, which resulted in a hardened surface layer. A similar observation has been reported in the use of some agricultural wastes as carburizers including palm kernel shells (Afolalu *et al.*, 2015), animal bones (Oyetunji *et al.*, 2012) and seashells (Aramide *et al.*, 2009).

The effective carburization process was further confirmed from the microstructural analysis. SEM images showed fine martensitic structures with uniformly dispersed carbides on the carburized surfaces with notable increase in the surface atomic percentage of carbon (at. % C) compared to the

control surface carbon of 15.35% as shown in Table 2. The enhanced hardness and wear resistance observed in the present work is supported by the results obtained by Duan *et al.* (2016) and Afolalu *et al.* (2017) which showed that carbide precipitation and refinement of the microstructure is enhanced at high carburizing temperatures.

Carbon diffusion was limited at lower carburizing conditions (850 °C) as evidenced by limited hardness improvement, especially for the shorter holding time duration. More successful, however, was an increase in the holding time to 90 minutes which enhanced carbon uptake but not as well as higher temperature treatments. This is in agreement with the temperature dependency of carbon diffusion reported by Elmi Hosseini and Li, 2016.

4. | Conclusion

This study is in agreement with the previous studies that walnut shell granules have been proven to be a good carburizing medium for M2 HSS

single point cutting tools. Walnut shell granules and carburization samples of HSS cutting tool were successfully prepared before carburization. Process of carburization was conducted at different temperatures and holding time and it is seen that the surface properties of the cutting tools were improved. The mechanical tests showed that the samples that were carburized had higher hardness values than the original

sample, which meant that carbon diffused into the surface of the tool.

Furthermore, characterization through SEM-EDS analysis confirmed changes in the microstructure and verified the increase in carbon content after carburization. These results show that all the stated objectives of the research were successfully achieved.

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