In this study, the effect of Sodium Dodecylbenzene Sulfonate (SDBS) addition as a surfactant on the performance of the Printed Circuit Board (PCB) particle-dispersed quenchant in terms of thermal conductivity, particle stability, the microstructure and hardness of S45C medium carbon steel has been investigated. Conventional quenchants have fixed, uncontrollable cooling rates. Adding solid particles creates a thermal bridge, enabling adjustable cooling rates to address this limitation. The solid particles in the quenchant were synthesized from PCB. The surfactant helps to improve particle dispersion and avoid agglomeration by modifying the surface tension between the particles and the fluid. PCB particle-dispersed media have been prepared and used as quenchants to study the effect of PCB dispersion, and its concentrations on the heat transfer rate during quenching. Based on this research results, particle stability measurement by zeta potential shows the stability improvement up to –21.53 mV after 7 wt % of surfactant addition, compared to distilled water. Due to the better particle dispersion, the thermal conductivity of the quenchant is also improved by 39 %, maximized at 0.82 W/mK when compared with the quenchant without surfactant at only 0.61 W/mK. Furthermore, the quenched steel hardness also increases by 29 %, maximized at 58 HRC at 7 wt % surfactant and 0.3 wt % PCB particles composition. The Dispersed PCB particles in the quenchant allow the heat flow from high to lower temperature efficiently. The experimental results show that a water-based quench medium with PCB particle dispersion is an alternative quench medium to obtain a more controlled cooling rate in steel heat treatment and is one solution for utilizing PCB electronic waste

Keywords: waste printed circuit board, sodium dodecylbenzene sulfonate, heat treatment, quenching process, S45C medium carbon steel

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IDENTIFYING THE EFFECT OF SODIUM DODECYLBENZENE SULFONATE SURFACTANT AND DISPERSED PCB-BASED PARTICLES AS A NOVEL HEAT TREATMENT QUENCHANT ON THE HARDNESS OF S45C MEDIUM CARBON STEEL

Wahyuaji Narottama Putra
Corresponding author
Master of Engineering*
E-mail: wahyuaji@ui.ac.id
Myrna Ariati
Professor of Metallurgy and Materials Engineering*
Eddy Sumarno Siradj
Professor of Metallurgy and Materials Engineering*
Bambang Suharno
Professor of Metallurgy and Materials Engineering*
*Department of Metallurgy & Materials Engineering
Universitas Indonesia
Margonda Raya str., Pondok Cina, Kecamatan Beji, Kota Depok, Jawa Barat, Indonesia, 16424

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1. Introduction

Heat treatment of steel is an important process where steel is rapidly cooled from high temperature to increase the strength and hardness through Martensite phase transformation [1]. Rapid cooling in this process is conducted using a quenchant. However, quenchant selection is also very important as different types of quenchant offer different cooling rates. Furthermore, improper cooling rates could have a negative impact on the quenched steel. Slow quenching could result in low hardness due to non-uniform Martensite formation. Meanwhile, quenching with excessively high cooling rates will crack the still because of high thermal shock during quenching.

The types of quenchants normally used are water, salt baths, brine solutions, vegetable oils and recently nanofluids. Water and brine were used as quenchants. Thus, the factors affecting the heat transfer rates during quenching have been studied by many researchers and plenty of literature is available [2, 3]. Recently, research using particle-dispersed quenching media was conducted because of their better heat transfer performance compared to conventional quenchants. Some used Carbon nanotube (CNT) nanofluids as quenchants and found that the method of preparation played a vital role in determining the heat transfer rates during quenching [4]. Also, some studied the effect of CNT concentration ranging from 0.25 to 1.0wt % in CNT nanofluids and agitation on heat transfer rates during quenching [4]. They found that the peak heat flux increased with CNT concentration until 0.5wt % and then decreased with a further increase in CNT concentration. However, the researchers have not yet analyzed the impact of Printed Circuit Board (PCB) particle-dispersed quenchant on the metallurgical and mechanical properties of steels.

Fast technology development results in many devices being produced every day. Many of these devices have a relatively short lifetime. Therefore, electronic waste is becoming an increasingly serious problem [5]. It is already common that one method to recycle e-waste is by reducing its size into small particles. Waste Printed Circuit Board (PCB) is one type of e-waste that is very concerning for the environment due to its huge amount. The use of PCB particles as a particle-dispersed quenching medium is one method for recycling electronic waste.

The main challenge for dispersing particles in a fluid is particle agglomeration. To have an improvement in the thermal conductivity of the quenchant, particle agglomeration must be avoided. Moreover, agglomerated particles tend to settle quickly, resulting in a non-uniform quenchant. To avoid this phenomenon, a surfactant is important to modify the particles' surface tension and disperse them better [6]. One type of commonly used surfactant is Sodium Dodecylbenzene Sulfonate (SDBS). Therefore, it is crucial to observe the effects of surfactant addition and PCB particles in the particle-dispersed surfactant on its performance to increase the strength of the quenched steel.

2. Literature review and problem statement

The papers [3, 7] present the results of quenching simulations and experiments. It is discussed that traditional quenching methods, such as using water, oil, and polymer-based solutions, face challenges due to fixed cooling rates during quenching for each quench medium. The fixed cooling rate characteristic makes it difficult to obtain a proper cooling rate, and often results in thermal gradients, causing cracks, warping, or distortions that compromise the steel's performance. Therefore, controlling the cooling rate in the quenching medium becomes very important. To overcome the cooling rate problem, both papers also suggest the utilization of particle-dispersed quench medium. However, the particles used in the papers are advanced and quite costly such as Carbon Nanotubes. Therefore, this would pose a problem if applied in the real heat treatment industry. Other options of more affordable particles are very crucial. For this reason, this research observes the possibility of using PCB particles as dispersed particles.

The paper [8] shows that fine-sized particles tend to agglomerate when dispersed in a fluid. This paper discussed the importance of surfactants to modify the surface tension of a particle to increase its stability. The mentioned paper, however, only focused on the characterization of the effect of surfactant addition. It does not elaborately explain the connection between surfactant addition and thermal conductivity in a quench medium.

For a quench medium, agglomeration could become a problem as well. Particle instability in the quenchant can lead to inconsistent quenching performance and reduced efficiency. This is a significant challenge in utilizing particles within quenching fluids, which is ensuring their stable dispersion. One way to overcome this problem is by surfactant addition. The addition of surfactants like sodium dodecylbenzene sulfonate (SDBS) becomes particularly important, as they help maintain a stable suspension of particles in the quenchant [7]. The addition of SDBS has been found to improve the wetting properties of quenching fluids by reducing their surface tension [9]. This allows for a more uniform cooling process, reducing thermal stress and minimizing the likelihood of cracking. SDBS, as an anionic surfactant, also plays a crucial role in stabilizing dispersed particles within the quenchant, preventing agglomeration that can cause uneven cooling rates. Stabilized particles due to surfactant addition in quenchants could increase its thermal conductivity and improve heat transfer [10]. By preventing agglomeration, SDBS ensures a uniform cooling process, which is crucial for reducing internal stresses and achieving the desired mechanical properties in steel. This, in turn, influences microstructure transformations, leading to improvements in the hardness and durability of steel components.

One innovative approach gaining attention involves repurposing electronic waste, particularly printed circuit boards (PCBs), as a source of particles for quenching media. PCBs contain various metals and compounds that could be utilized to enhance heat transfer during quenching.

The papers [11, 12] discussed waste PCB utilization by processing into small particles. The obtained small particles of waste PCB are normally then leached to produce a precious metal. Meanwhile, the rest of the PCB compound is still underutilized and disposed of in landfills. Therefore, the papers still don't offer any solution to utilize waste PCB with precious metals already extracted.

One option to reduce waste PCB sent to landfill disposal is by using it as dispersed solid particles in a quench medium. It is already well known that solid particles have higher thermal conductivity than a fluid [13]. Hence, adding solid particles in a quench medium could increase its overall thermal conductivity. Using particles derived from electronic waste not only leverages their thermal properties but also addresses the growing concern over e-waste recycling, aligning with sustainability goals [14]. This approach not only provides a potential enhancement in steel hardness but also offers a novel method to repurpose waste materials, turning them into valuable resources for industrial applications.

All this allows us to assert that it is expedient to conduct a study on the combined use of SDBS surfactant and PCB-derived particles as a novel quenchant for medium carbon steel, specifically S45C steel. It is necessary to explore whether this innovative quenchant can improve the hardness and overall mechanical properties of steel while also contributing to sustainable waste management.

3. The aim and objectives of the study

The aim of this study is to determine the effectiveness of using PCB-based particles, combined with the SDBS surfactant, in creating a novel quenchant to improve the hardness of S45C medium carbon steel.

To achieve this aim, the following objectives are accomplished:

– to observe the effect of leaching and milling on PCB-based particles;

– to evaluate the stability and thermal conductivity of PCB-based particle-dispersed fluid;

– to analyze the microstructure of S45C steel after the quenching process.

4. Materials and methods

The object of the study is the properties of S45C medium carbon steel after heat treatment. It is hypothesized that adjusting the amount of solid particle addition could control the thermal conductivity and thus optimize the cooling rate of the quenchant. By using particles sourced from PCBs, this research not only optimizes the quenching process but also promotes an environmentally friendly solution that aligns with circular economy principles. The findings have the potential to transform traditional heat treatment practices by reducing dependence on conventional quenchants that may have environmental and economic drawbacks, thereby fostering greener industrial processes.

The main sample of this research is PCBs as a source of dispersed particles in the quenchant, and S45C steels for the sample in the quenching process. Both PCB and S45C steel are new, commercially available, generic, and unbranded type. In this research, a new unused commercially available PCB was used to avoid any unnecessary contamination. It is assumed that the unused PCB could represent waste PCB without any significant difference. Furthermore, the usage of unused PCB also simplifies the sample preparation steps by avoiding any cleaning process. The PCB was bought in a 10×20 cm board shape (Fig. 1). To prepare for further treatment, the PCB was rough milled using a large steel ball to create coarse particles (Fig. 2). For the milling process, the equipment used was an NQM-4L planetary ball milling machine from Shenzhen, China. A 500 ml SUS 304 stainless-steel jar was used to contain the PCB sample during milling. In rough milling, a stainless-steel ball with a diameter of 20 mm was used. Rough milling was conducted at 500 rpm for one hour.

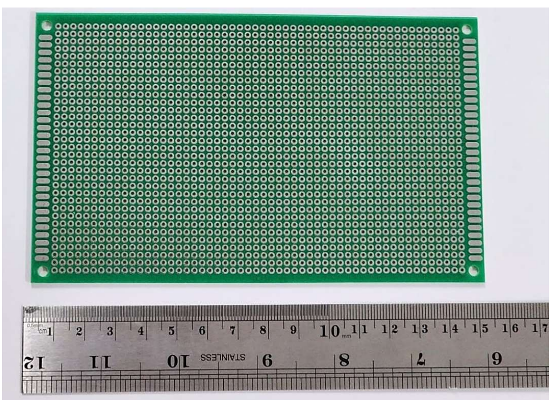

Fig. 1. Commercially available Printed Circuit Board

Fig. 2. Coarse Printed Circuit Board-based particles obtained by rough milling

The PCB particles were then leached to reduce the metal fraction content, simulating the extracted waste PCB. Leaching also helps to dissolve the epoxy resin, which binds the fiberglass [12]. The leaching process was done using 1M HCl with stirring for 24 hours [15], using a generic beaker glass on top of a magnetic stirrer. After leaching, the PCB was pyrolyzed to change the polymer used in the PCB into a charcoal-like substance (Fig. 3). The charcoal-like substance is more brittle, hence might help the milling process later. The pyrolysis treatment was conducted in a Nabertherm tube furnace for 15 minutes at 500 °C in the Argon gas to create an Oxygen-free environment. The Argon gas flow was 5 liters per minute. Subsequently, the PCB was milled to reduce the particle size (Fig. 4). For the particle reduction milling, the same planetary ball milling machine and jar were utilized. However, the stainless-steel ball used for particle reduction has a diameter of 3 mm. The dry milling process was conducted for 20 hours at 500 rpm. A typical 10:1 ball to powder ratio was used.

Fig. 3. Printed Circuit Board-based particles after the pyrolysis process

Fig. 4. Planetary ball milling process on the Printed Circuit Board-based particles

The characterization of PCB particle morphology was conducted using Scanning Electron Microscopy (SEM). The SEM instrument used in this research was FEI Inspect 50. For the electron microscopy observation, a small amount of PCB particles was placed on top of a sample stub with a carbon tape. Because the PCB particles are not conductive, a layer of Au-Pt was then coated on the sample using a sputter coater, to prevent charging defects during SEM observation.

For the chemical composition of the particles, X-Ray Fluorescence (XRF) was employed using an Aeris XRF instrument from PANalytical. In this observation, PCB particles were placed on a sample plate. The X-ray from the instrument will radiate the PCB particles, exciting the innermost electron in the particle, which leaves the orbital creating a vacancy. The electron from the outer orbital then fills the vacancy while emitting fluorescence radiation, which can be used to identify the chemical composition of the sample.

The particle size was measured using Particle Size Analysis (PSA), coupled with Zeta Potential to observe the particle stability in the fluid. The equipment used for both PSA and Zeta Potential measurement was a Horiba SZ-100 nanoparticle analyzer. The PCB sample was dispersed into distilled water and inserted in a cuvette for this observation. Dynamic Light Scattering method was applied for the measurement. In this method, a laser is irradiated toward the particles, and the angle of scattering was measured to determine the particle characteristics.

To synthesize the particle-dispersed quenchant, the milled PCB particles were added to distilled water as a base fluid. The concentration of the particles was (in weight percent) 0.1, 0.3, and 0.5. As mentioned earlier, a surfactant was added to improve the particle dispersion. The SDBS addition was 3 %, 4 % and 7 %, respectively in each particle variation. The surfactant was then assumed to have a uniform mixture after the ultrasonic bath. Each quenchant variation was checked for thermal conductivity. Thermal conductivity was measured using the KD2 Pro Thermal Properties Analyzer. This equipment operates based on the transient hot-wire method (THW), where a small probe heats the surrounding water and measures the resulting localized temperature increase. For the measurements, 100 ml of quenchant was placed in a glass beaker. The temperature of the quenchant was maintained at room temperature (approximately 26 °C) using a temperature-regulated water bath. This precaution ensured that the quenchant's temperature remained stable and did not rise excessively during the measurement, which could otherwise affect the accuracy of the results.

For the heat treatment and quenching experiment, S45C medium carbon steel was austenitized and quenched. The sample dimensions are shown in Fig. 5. The steel composition was checked by Optical Emission Spectroscopy (OES). For this research, Foundry-Master Xpert was used as a spectroscope instrument. The wide flat surface of the steel sample was sanded using #300 sandpaper to remove any contaminants and smooth out the cutting mark. Subsequently, the prepared side of the sample was placed on the OES equipment, and then a high voltage will spark the sample.

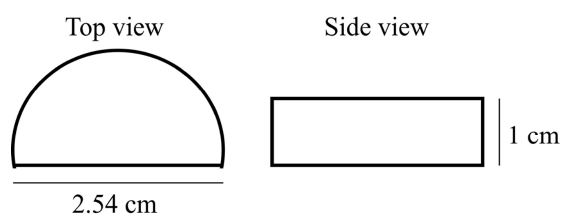

Fig. 5. Dimensions of the S45C steel sample

Because of the spark, the electron in the sample will be excited and emit a certain unique wavelength for each element. This wavelength can be used as a base for composition identification. The composition results are shown in Table 1. The sample dimensions ensure the efficiency of the austenization duration, while still provide ample space for hardness testing. The composition test confirms that the sample was S45C.

Austenization was conducted at 900 °C for 1 hour, followed by quenching using each variation of the quenchant (Fig. 6). From the figure, it can be seen that the heating rate was roughly at 10 °C/minute. Preheating at 500 °C was done to avoid any thermal shock.

Table 1

Chemical composition of the S45C steel sample

Element	Weight, %
Fe	98.1
C	0.45
Si	0.27
Mn	0.71
P	0.03
S	0.07

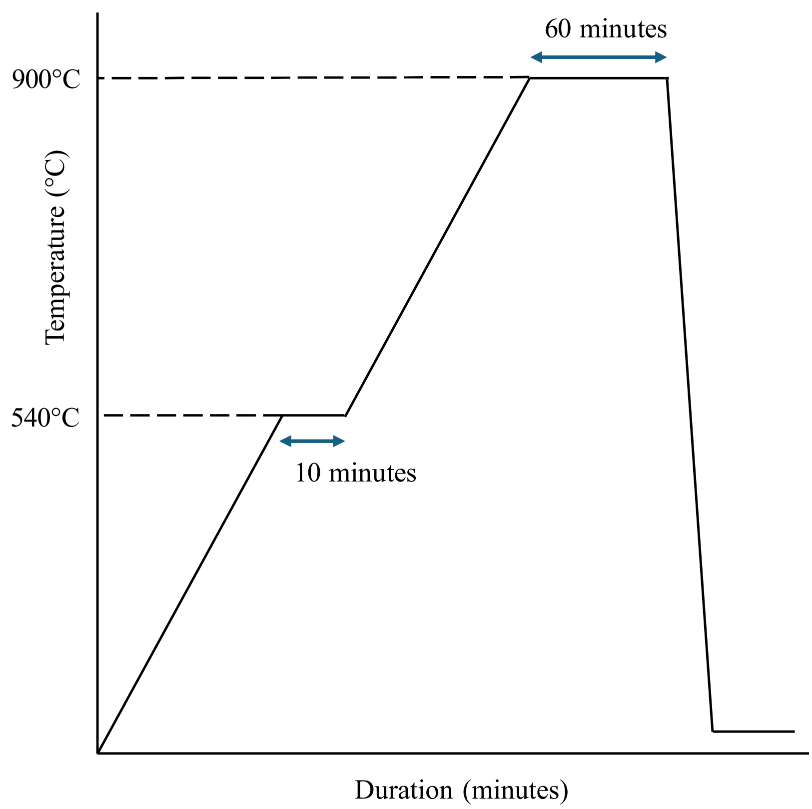

Fig. 6. Heat treatment profile for steel quenching

After the heat treatment process, the sample underwent a standard metallographic preparation route, including mounting, grinding, and polishing. The steel hardness and microstructure were then checked using a Rockwell hardness tester and an Optical microscope to observe the different performance of the quenchant. The microstructure analysis was performed using an Olympus Inverted Metallurgical Microscope BX41M-LED. To reveal the microstructure, a freshly prepared 2 % Nital solution (composed of 2 ml nitric acid and 98 ml of 75 % alcohol) was utilized as an etchant. The etching duration ranged from 5 to 30 seconds, depending on the sample. Rockwell hardness testing was carried out using the Qualirock Digital Hardness Tester, following the ASTM E18 standard. In this testing, an indentation is produced by a load from the indenter on the surface of the steel sample. After that, the permanent depth of the indentation is measured by the equipment. The indentation will be shallower on the harder sample.

5. Results of the research on printed circuit board-based particles with sodium dodecylbenzene sulfonate

5. 1. Observation on leaching and milling effects on printed circuit board-based particle synthesis

Table 2 shows the XRF results of leached PCB particles. The most significantly reduced element was Magnesium, from 25 % to 8 %. The other elements seemed to be fluctuating even though not significantly. Chlorine, on the other hand, increased significantly due to leaching using HCl. The leaching process reduced the metallic element content in the PCB to simulate the extracted waste PCB. During the leaching process, metals react with HCl, creating metal chlorides [15]. The most significant reduction occurred for Magnesium metal, as it is easier to form $MgCl_2$ compared to other metal chlorides. From the same study, it is mentioned that HCl leaching showed the most optimum metal reduction compared with other acids such as HNO_3 or H_2SO_4 [15]. However, another study also found that using aqua regia, some metals digestion is more satisfactory [14]. The usage of HCl in this research considers the safer leaching waste effect on the environment.

Table 2

X-Ray Fluorescence results for Printed Circuit Board-based particles

Element	Concentration before leaching (%)	Concentration after leaching (%)
Mg	25.975	8.277
Al	8.391	8.361
Si	35.099	37.808
S	0.686	0.676
Cl	0.273	13.323
K	0.2	0.214
Ca	23.184	20.846
Ti	0.245	0.281
Cr	0.229	0.235
Mn	464.7 (ppm)	606.3 (ppm)
Fe	1.376	1.484
Ni	664.6 (ppm)	578.7 (ppm)
Cu	2.374	4.753
Br	0.116	0.151
Sr	0.293	0.356
Ag	0.237	0.286
Sn	0.245	0.748
Ba	0.789	1.703
Pb	0.174	0.381

However, in general, the metallic content in the particles may help to increase the thermal conductivity of the quenchant. Solid metallic particles generally have higher conductivity compared to non-metallic ones [13]. However, due to the greater weight of metallic particles, they tend to settle faster than non-metallic particles.

As mentioned earlier, the leached PCB particles were pyrolyzed and milled using a planetary ball mill. The average particle size was determined by PSA. Before milling, the particle size averaged at 1,035 nm. The particle size was reduced to 572 nm after milling. Hence, it can be concluded that the milling process could reduce the particle size by up to 44 %. The morphology of the milled particles is shown in Fig. 7. From the SEM image, the particle shape is mainly granular.

The granular shape of the particles is a result of the shear and impact force between the ball mill, mill jar, and the PCB particles themselves. Although there are still rectangular-shape particles, probably from the fiberglass particles, the majority of granular particles indicate that the milling process was conducted successfully.

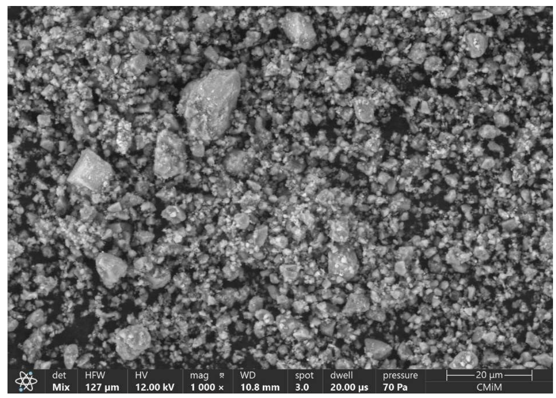

Fig. 7. Morphology of milled Printed Circuit Board particles

5. 2. Evaluation of the stability and thermal conductivity of a printed circuit board-based particle-dispersed fluid

The synthesized PCB particles were then used to create a quenchant. SDBS was added as a surfactant to help and improve particle dispersion. The dispersion of the particles was measured using zeta potential. Table 3 shows the effect of surfactant addition in the quenchant with 0.5 % particles. It shows that the increasing concentration of the SDBS surfactant; increases the zeta potential of the quenchant. The result is similar to another report where particles are more stable with the increasing content of the SDBS surfactant [6, 16]. Higher zeta potential means better stability, where particles could disperse longer without precipitation.

Table 3

Zeta potential analysis of Milled PCB particle-dispersed fluid stability

PCB particle content (weight %)	SDBS content (%)	Zeta potential (mV)
0.5	0	–16.1
	3	–18.1
	5	–20.13
	7	–21.53

As a quenchant, thermal conductivity becomes an important characteristic. Thermal conductivity measurement was done on all quenchants. The measurement is shown in Fig. 8. In the figure, the most optimum thermal conductivity was obtained at 0.82 W/mK for the quenchant with 0.3 % PCB particles and 7 % SDBS surfactant addition. Standard room-temperature distilled water has a thermal conductivity of around 0.59 W/mK.

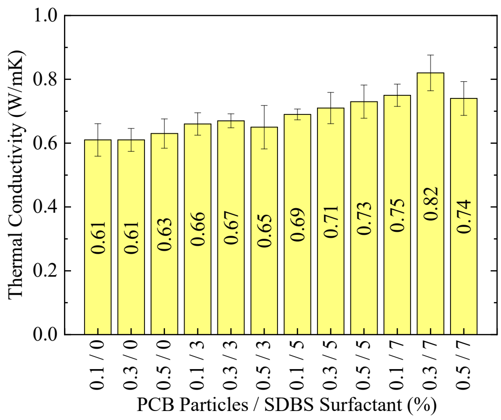

Fig. 8. Thermal conductivity of the quenchant with dispersed Printed Circuit Board-based particles

Therefore, the additional particles and surfactant increased the thermal conductivity up to 39 %. A decrease in the thermal conductivity was found at 0.5 % PCB particles with 3 % and 7 % SDBS. The result is quite similar to previous research using multi-walled carbon nanotubes (MWCNT) as nanoparticles and different surfactants [10]. It might suggest that the phenomenon is similar, where a higher percentage of PCB-based particles was not fully compatible with SDBS as a surfactant, creating agglomeration and lowering thermal conductivity. Agglomeration occurred because of the formation of micelles from the bulk surfactant [17]. These micelles reduce the ability of the surfactant to modify the particle's surface tension [18].

5. 3. Microstructure analysis of S45C steel after the quenching process

Before any heat treatment, S45C steel has a very low hardness at 20 HRC. To support the hardness results, standard metallography practice was conducted to reveal the microstructure. All samples were mounted, ground, polished, and lastly etched using 2 % Nital solution. The microstructure of this steel is shown in Fig. 9. As expected, the microstructure consists of Ferrite and Pearlite phases [7]. Heat treatment and quenching were conducted to improve the characteristics, especially the hardness of the steel.

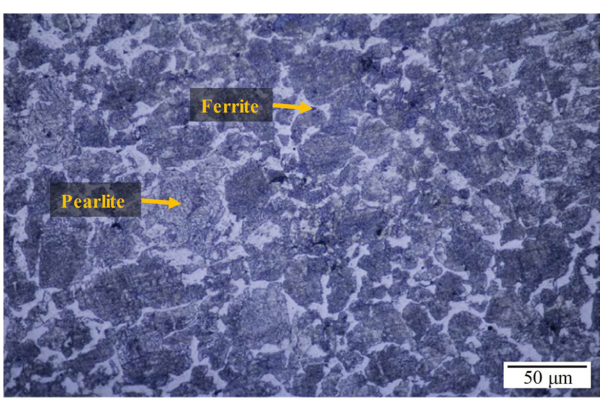

Fig. 9. S45C microstructure before heat treatment showing Ferrite and Pearlite phases

The first steel sample was quenched in distilled water to compare the effects of PCB-based particles and surfactant addition. The microstructure of the water-quenched sample is shown in Fig. 10. Because of the rapid cooling, the microstructure consisted of Bainite and Martensite phases. The hardness value of the steel was increased up to 43 HRC. The increasing hardness after quenching is a common knowledge and has been reported by many studies [19].

The other samples were then quenched with quenchants added with different variables of PCB particles and surfactant addition. Fig. 11 shows the hardness of the steel after quenching in different quenchants. From Fig. 11, it appears that in general, the higher amount of surfactant addition could increase the hardness of the steel.

The highest hardness was achieved at 58 HRC for the

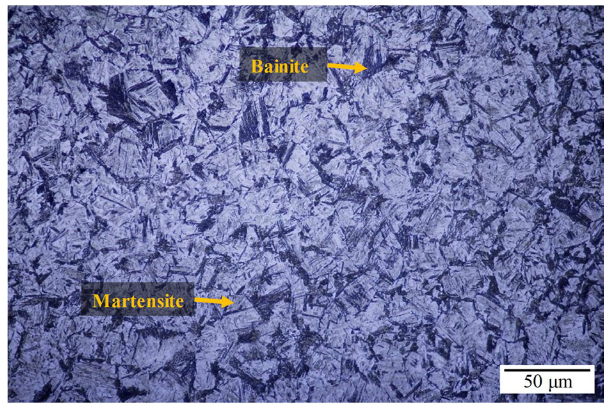

Fig. 10. S45C microstructure after quenching with distilled water

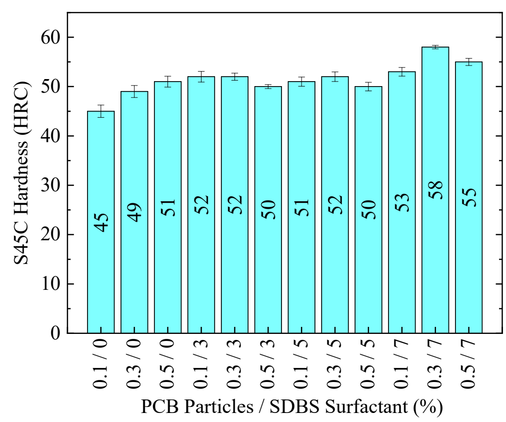

Fig. 11. Hardness result of S45C steel quenched in different quenchants with dispersed Printed Circuit Board-based particles

sample quenched in 0.3 % PCB particles and 7 % SDBS. This hardness number is an improvement of roughly 35 % compared with the steel quenched in distilled water. The result suggests that the optimum ratio between particles and surfactant provides the best improvement in steel hardness. Excessive particles or surfactant could result in agglomeration and lower steel hardness [4, 7].

On the other hand, without the surfactant, the particles tend to agglomerate and settle easily. Hence, there is only a few dispersed particles in the base fluid. This phenomenon is supported by the result where the surfactant was not added to the quenchant. The lowest achieved hardness for the steel quenched in PCB-based particles was 45 HRC. Even this lowest hardness was still 4 % higher than that of steel quenched in distilled water.

The hardness result is in line with the thermal conductivity result. Higher thermal conductivity would provide a faster cooling rate, hence higher steel hardness. Lower thermal conductivity, for example, on the sample with more surfactant, resulted in lower steel hardness. Therefore, it can be concluded that the thermal conductivity of the quench medium affects the cooling rate and the final quenched steel hardness.

Microstructure observation was conducted to support the hardness of the steel sample. The sample was also ground, polished, and etched using 2 % Nital solution. Fig. 12, 13 show the microstructure of the steel with the lowest and highest hardness, respectively. Each sample contains Martensite and Bainite phases. The only difference was the amount of each phase.

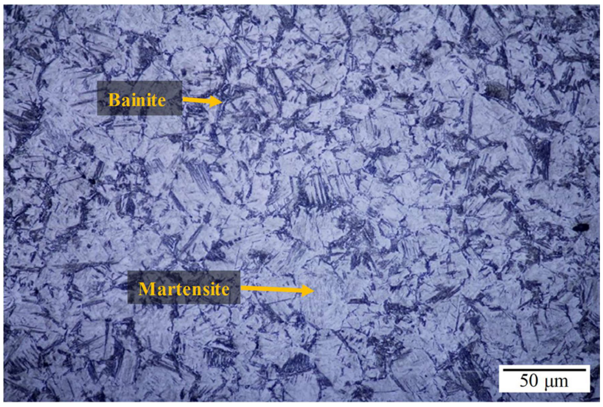

Fig. 12. Microstructure of steel quenched with 0.1 % Printed Circuit Board-based particles without surfactant

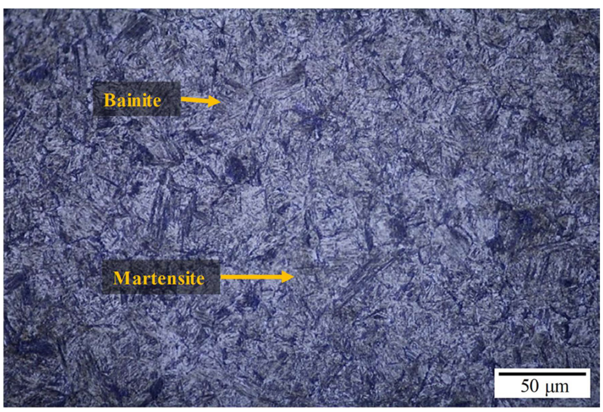

Fig. 13. Microstructure of steel quenched with 0.3 % Printed Circuit Board-based particles and 7 % surfactant

As expected, the microstructure for the steel quenched in the quenchant with 0.1 % PCB without surfactant has a less dense Martensite phase. Meanwhile, the steel quenched in the quenchant with 0.3 % PCB and 7 % surfactant has a denser Martensite phase, hence the higher hardness. In the sample with the highest hardness, the Martensite phase was denser [20].

6. Discussion of the results of research on the effect of sodium dodecylbenzene sulfonate addition as a surfactant in the printed circuit board-based particle-dispersed quenchant on the hardness of S45C steel

The leaching process in this study was designed to simulate the actual condition of waste PCBs by reducing their metal content. HCl was chosen as the leaching agent due to its efficiency in removing metallic elements, particularly magnesium, as indicated in Table 2. Its use aligns with the environmental objectives of this study because it produces less hazardous waste compared to alternatives such as aqua regia. The paper [12] reported that aqua regia has more comprehensive metal removal capabilities, however, its byproduct poses significant environmental risks. The mentioned risks would contradict the sustainable approach targeted in this research. By carefully selecting HCl, the study achieved a balance between effective metal removal and environmental safety, emphasizing its practicality in real-world applications where minimizing pollution is very crucial.

Following the leaching process, pyrolysis was employed to enhance the carbon content of the PCB particles. This step converted the resin components of the PCB into char, significantly increasing the thermal conductivity of the particles because of the high carbon content. The residual metallic elements in the pyrolyzed PCBs further contributed to this improvement, creating a mixture of particles with a high thermal performance profile. This stage of the process not only improved the functional properties of the material but also highlighted the potential of pyrolysis as a value-adding step in repurposing electronic waste. The enhanced thermal conductivity of the particles is critical for their role in the quenchant, as it directly influences the efficiency of heat transfer during quenching. The thermal conductivity of particles is reported by [13], stating that solid particles always have higher conductivity than a fluid.

The next step involved size reduction through planetary ball milling, which reduced the particle size to an average of 572 nm, as shown in Fig. 7. This reduction represented a 44 % decrease from the initial size, demonstrating the efficiency of the process. The result is similar to the paper [11] where the final particle size is in the range of 500 nm by using a disk mill. Planetary ball milling is a widely used and cost-effective method for particle size reduction, offering a balance between simplicity and performance [14]. However, its effectiveness depends heavily on parameters such as milling duration, rotational speed, and the ratio of ball to powder. Despite these efforts, the resulting particle size remained in the range of hundreds of nanometers. While this size is acceptable for many applications, it poses challenges for uniform dispersion in fluid media and can increase settling speed, potentially affecting long-term stability. These challenges mean the need for further adjustment in milling techniques to achieve smaller, more uniform particles for even better performance. Nevertheless, the milling process shows its potential to reduce the PCB into small particles, which can be utilized as dispersed particles in the quenchant.

To address the dispersion challenges, the study utilized SDBS as a surfactant, which significantly improved the zeta potential of the particle-dispersed fluid to –21.53 mV (Table 3). This improvement ensured that the particles remained stable and non-agglomerated, which is critical for maintaining consistent thermal conductivity. Stable dispersions allow for efficient heat transfer, as the particles provide continuous pathways for the heat to move from high-temperature regions to cooler ones within the fluid. The enhanced stability provided by SDBS minimized agglomeration, ensuring a uniform distribution of particles throughout the fluid. This stability is essential for achieving continuous pathways for heat transfer and maintaining the performance of the quenchant over time. Hence, it is shown that SDBS addition could contribute to particle stability. The SDBS role in increasing particle stability is also supported by the paper [6], stating that SDBS addition increases the zeta potential of the fluid.

The data in Fig. 8 confirm that adding 7 % SDBS increased the thermal conductivity of the quenchant to 0.82 W/mK, which is comparable to the performance of more advanced and costly materials such as multi-walled carbon nanotubes (MWCNT) [10]. Unlike MWCNT, however, the PCB-based particles are more sustainable and environmentally friendly, offering a viable alternative for heat treatment applications where cost and sustainability are key considerations. The improved thermal conductivity shows the importance of SDBS surfactants in enhancing heat transfer efficiency. Stable dispersions allow for continuous and effective pathways for thermal energy movement, demonstrating the quenchant's potential in industrial heat treatment applications.

The improved performance of the particle-dispersed quenchant was further validated through microstructure observation and hardness testing of the quenched steel. Before quenching, the steel has a microstructure of Ferrite and Pearlite phases, shown in Fig. 9. These phases transform after quenching into Martensite and Bainite (Fig. 10). Martensite and Bainite phases have higher hardness. The hardness testing confirms this phase transformation. As shown in Fig. 11, the hardness of the steel increased linearly with the thermal conductivity of the quenchant. The steel microstructure in Fig. 12, 13 shows a denser Martensite phase, hence higher hardness. The paper [7] also reported the Martensite and Bainite phase transformation after quenching, similar to this study. This relationship shows the importance of thermal conductivity in determining the effectiveness of quenching processes. Furthermore, this relationship highlights the crucial role of improving particle stability by SDBS surfactant addition in determining the effectiveness of quenching processes. When compared to traditional quenchants such as water or oil, the particle-dispersed quenchant demonstrated a more significant improvement in steel hardness. This result highlights the potential of the proposed quenchant for industrial heat treatment processes.

Despite these promising findings, the study is not without limitations. One major limitation is the relatively large size of the particles after milling, which could impact the uniformity of dispersion and the settling behavior over time. While the addition of SDBS mitigated these issues to some extent, achieving smaller particle sizes would provide further benefits, including a larger surface area for heat transfer and improved fluid stability. Additionally, the disadvantage of this study is lacked precise thermal conductivity data for the PCB particles themselves. The mixed and loose nature of the PCB material complicates the direct measurement of this property, creating a gap in the evidence base. Future research could explore this disadvantage by compressing the particles into solid forms to facilitate accurate thermal conductivity measurements, though care must be taken to avoid air entrapment, which could interfere with the results.

There are several directions for improvement of this research. Achieving finer particle sizes through advanced milling techniques, such as shaker milling, could enhance the thermal and dispersion properties of the quenchant. Additionally, exploring alternative surfactants, such as Cetyl Trimethyl Ammonium Bromide (CTAB) or Polyethylene Glycol (PEG), could provide a broader understanding of how different stabilizers impact particle dispersion and overall fluid performance. Other than the mentioned technical improvements, a deeper investigation into the environmental impact of the synthesized PCB particles, such as a life-cycle assessment, would strengthen the sustainability claims of this study and highlight its broader implications for waste management and green technology. Finally, exploring the practical applications of this quenchant in industrial settings would provide valuable insights into its scalability and potential to replace conventional quenching media.

The findings of this study demonstrate a potential for practical applications in the industry of steel heat treatment processes, particularly where improving mechanical properties, such as enhanced hardness is essential. This quenchant is also suitable for industries focusing on sustainability, in which environmental impact is a critical consideration.

The proposed quenchant is, nevertheless, optimized under specific conditions. For the real application of the quenchant, the parameter such as the particle and surfactant concentration may require to be adjusted depending on the aim to be achieved. In the future, the adoption of this quenchant has the potential to improve the mechanical properties of steel, reduce the operational cost, while minimizing the environmental impact.

7. Conclusions

1. The study demonstrated that the leaching process using HCl effectively reduced the metallic content, particularly magnesium, with its concentration decreasing from 25.9 % to 8.3 %. This result aligns with previous findings that HCl is efficient in reducing specific metal concentrations while being relatively safer for the environment. Additionally, the milling process using a planetary ball mill successfully reduced the particle size from 1,035 nm to 572 nm, indicating a 44 % reduction.

2. The addition of SDBS surfactant significantly improved the stability of the PCB particle-dispersed fluids, as evidenced by the increase in zeta potential from –16.1 mV to – 21.5 mV with increasing surfactant concentrations. This indicates better particle dispersion and reduced agglomeration, resulting in longer stability of the quenching fluid. The thermal conductivity of the optimized quenchant reached 0.82 W/mK, representing a 39 % increase over distilled water (0.59 W/mK). However, at higher particle concentrations, agglomeration was observed, which decreased thermal conductivity due to ineffective surfactant-particle interaction.

3. The quenching process using the PCB particle-dispersed quenchant resulted in an improvement in the hardness of S45C steel, achieving a maximum hardness of 58 HRC compared to 43 HRC for water-quenched samples. Furthermore, the microstructural analysis revealed a dens-

er martensitic phase in the quenched steel when using the PCB-based quenchant, compared to a less dense mixture of Bainite and Martensite in water-quenched samples. This result highlights the potential of using recycled e-waste particles not only for sustainability but also for achieving enhanced mechanical properties in heat-treated steels.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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