Optimization of Gear Sprocket Surface Hardness through a Combination of Ice Water Quenching and Shot Peening with Pressure Variations

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ABSTRAK

Gear sprocket merupakan komponen sistem transmisi yang bekerja di bawah beban torsi dan gesekan berulang, sehingga rentan mengalami keausan pada permukaannya. Untuk meningkatkan ketahanan aus, diperlukan perlakuan yang mampu memperkeras lapisan permukaan tanpa mengubah dimensi secara signifikan. Penelitian ini bertujuan mengevaluasi pengaruh kombinasi proses *quenching* menggunakan media air es dan variasi tekanan *shot peening* terhadap kekerasan permukaan serta perubahan struktur mikro pada *gear sprocket* berbahan baja karbon sedang. Sampel dipanaskan hingga suhu austenitisasi 850 °C selama 15 menit kemudian didinginkan cepat dengan media air es. Selanjutnya dilakukan *shot peening* selama 20 menit menggunakan *steel shot* berdiameter 0,6 mm pada tekanan 5, 6, 7, dan 8 bar. Pengujian kekerasan permukaan dilakukan dengan metode Vickers (HV), sedangkan pengamatan struktur mikro menggunakan mikroskop optik setelah etsa Nital 2% untuk mengidentifikasi perubahan fasa. Hasil penelitian menunjukkan bahwa perlakuan *quenching* air es meningkatkan kekerasan permukaan dari 199 HV menjadi 329 HV atau naik sekitar 65% dibanding kondisi awal. Kombinasi *quenching* dan *shot peening* menghasilkan peningkatan kekerasan menjadi 404 HV, 454 HV, 487 HV, dan 552 HV masing-masing untuk tekanan 5, 6, 7, dan 8 bar, dengan peningkatan tertinggi mencapai 177% terhadap kondisi awal. Pengamatan struktur mikro menunjukkan terbentuknya fasa martensit halus pada lapisan permukaan setelah *quenching* serta terbentuknya lapisan terdeformasi akibat tumbukan partikel pada spesimen *shot peening*. Dengan demikian, kombinasi *quenching* air es dan variasi tekanan *shot peening* terbukti efektif meningkatkan kekerasan permukaan dan memperhalus struktur mikro *gear sprocket*, sehingga metode ini berpotensi diterapkan untuk meningkatkan ketahanan aus komponen transmisi.

Kata kunci: *Gear sprocket*; *hardness Vickers*; *quenching* air es; *shot peening*; struktur mikro

ABSTRACT

The gear sprocket is a transmission system component that operates under repeated torsional and frictional loads, making its surface susceptible to wear. To improve wear resistance, a treatment is required to harden the surface layer without significantly altering its dimensions. This study aims to evaluate the effect of combining ice-water quenching and varying shot peening pressures on the surface hardness and microstructural changes of a medium carbon steel gear sprocket. The specimens were austenitized at 850 °C for 15 minutes and rapidly cooled using ice water. Subsequent shot peening was performed for 20 minutes using 0.6 mm diameter steel shots at pressures of 5, 6, 7, and 8 bar. Surface hardness was measured using the Vickers (HV) method, and microstructural observations were conducted with an optical microscope after 2% Nital etching to identify phase transformations. The results show that ice-water quenching increased the surface hardness from 199 HV to 329 HV, representing an increase of approximately 65% over the untreated condition. The combination of quenching and shot peening further enhanced hardness to 404 HV, 454 HV, 487 HV, and 552 HV at 5, 6, 7, and 8 bar, respectively, with the maximum improvement reaching 177% compared to the untreated specimen. Microstructural analysis revealed fine martensitic structures on the quenched surface and a plastically deformed layer produced by shot impacts. Therefore, the combination of ice-water quenching and shot peening effectively enhances surface hardness and refines the microstructure of gear sprockets, indicating its potential application in improving the transmission components wear resistance.

Keywords: Gear sprocket; ice-water quenching; microstructure; shot peening; Vickers hardness

INTRODUCTION

Transmission components are a crucial part of a vehicle's drivetrain, transmitting power from the rotational source to the drive wheels. One component directly involved in the transmission system is the sprocket gear, which operates continuously under repeated torque and friction loads. These operating conditions make the sprocket gear surface susceptible to wear and hardness loss, particularly in the tooth contact area [1]. Excessive wear can reduce power transmission efficiency and shorten component lifespan [2]. Therefore, increasing surface hardness is crucial for extending the lifespan of sprocket gears and maintaining stable performance [3].

Various methods have been developed to improve the surface hardness and wear resistance of medium-carbon steel commonly used in sprocket gears. One widely used method is heat treatment, such as quenching, to produce a hard martensite structure [4]. The type of cooling medium used in the quenching process significantly affects the cooling rate and the resulting microphases [5]. Ice water has the ability to rapidly cool, producing fine-grained martensite with high hardness [6], but is often accompanied by the risk of residual stresses and surface cracking if not combined with appropriate post-quenching treatments [7].

In addition to heat treatment, surface hardness can also be increased through mechanical surface treatments such as shot peening. This process works by impacting the material surface with high-speed metal grains, causing plastic deformation and producing compressive residual stress in the surface layer [8]. This compressive residual stress can inhibit crack initiation and increase resistance to wear and surface fatigue [9]. Variations in shot peening pressure directly affect the impact energy and the depth of the plastically deformed layer [10].

Several previous studies have shown that the combination of heat treatment and surface treatment can provide synergistic results in improving the mechanical properties of medium-carbon steel [11,12]. However, most previous studies have focused on shot peening after quenching with water or oil, while the use of ice water, which has a higher cooling rate, has not been widely studied. This research gap is important to explore because rapid cooling has the potential to produce a finer martensite microstructure, which, when combined with shot peening, can optimally strengthen the surface layer.

Based on this, this study was conducted to analyze the effect of a combination of ice water quenching and varying shot peening pressure on the surface hardness and microstructure of medium-carbon steel sprocket gears. This research is expected to provide a deeper understanding of the relationship between process parameters and changes in material mechanical properties, as well as offer an alternative, effective and cost-effective surface hardening method for automotive transmission components. The novelty of this research lies in the use of a combination of ice water quenching and varying shot peening pressure as a simultaneous effort to increase the hardness and refine the microstructure of medium-carbon steel sprocket gears, a finding not widely reported in previous research.

RESEARCH METHODS

The main material used in this study was a medium-carbon steel motorcycle sprocket gear. The material's chemical composition indicates Fe as the primary element, with small amounts of alloying elements such as C, Mn, and Si. The main equipment used included an electric furnace for the austenitization process, ice water at ±5°C as the cooling medium, a pneumatic shot peening machine, S-230 steel shot with a diameter of 0.6 mm, an air compressor with a maximum pressure of 10 bar, a micro-Vickers hardness tester, and an optical metallurgical microscope. The etching solution used was 2% Nital to highlight grain boundaries for microstructural observations.

The specimens were cut from the sprocket gear into rectangular shapes measuring ±15 × 15 × 5 mm. The specimen surfaces were cleaned using sandpaper and alcohol to remove dirt and oil. The quenching process was carried out by heating at an austenitization temperature of 850°C for 15 minutes using an electric furnace, then rapidly cooling in ice water to room temperature. After quenching, the specimens were dried and prepared for shot peening.

The shot peening process was carried out for 20 minutes at varying air pressures of 5, 6, 7, and 8 bar. The distance between the nozzle and the specimen surface was maintained at approximately 10 cm with a 90° impact angle. The impact medium, a 0.6 mm diameter steel shot, was directed evenly over the entire specimen surface using compressed air. After the treatment was completed, the specimens were cleaned and dried before being tested for hardness and microstructure.

Surface hardness testing was performed using a micro-Vickers hardness tester with a pressure of 0.98 N and a holding time of 15 seconds. Tests were performed on the specimen surface for each shot peening pressure variation

and the initial untreated condition. The hardness values obtained were then averaged for each condition to determine the effect of the combination of quenching and shot peening on surface hardness.

The treated samples were cut into cross-sections and then subjected to grinding, polishing, and etching using a 2% Nital solution. Observations were made using an optical metallurgical microscope with 5× and 50× magnification to identify phase changes and grain morphology. The main phases observed included ferrite, pearlite, and martensite. Comparison of the microstructure between untreated, after quenching, and after a combination of quenching and shot peening was used to analyze the relationship between microstructural changes and surface hardness increase.

RESULTS AND DISCUSSION

Results and Discussion of Chemical Composition Test

Chemical composition testing was conducted using optical emission spectroscopy (OES) to determine the levels of the main constituent elements in the sprocket gear material before treatment. The test results are shown in Table 1.

Table 1 Chemical Composition Test of Gear Sprocket

No.	Element	Test Sample	
		616/22-S1659 (%)	Standard Deviation
1.	C	0,094	0,0025
2.	Si	0,148	0,0089
3.	Mn	0,157	0,022
4.	P	0,335	0,119
5.	S	0,029	0,0024
6.	Cr	0,047	0,0052
7.	Mo	<0,0100	0,0045
8.	Ni	0,026	0,0027
9.	Cu	0,020	0,0005
10.	Al	<0,0050	0,00000
11.	Co	<0,0050	0,00000
12.	Mg	<0,0050	0,0002
13.	Nb	0,013	0,0029
14.	Ti	<0,0030	0,0009
15.	V	0,0081	0,0015
16.	W	<0,100	0,0021
17.	Fe	98,74	0,131

The 0.68% Mn content plays a significant role in increasing tensile strength and wear resistance by forming a solid solution with Fe and enhancing hardenability during quenching. The 0.21% Si element acts as a deoxidizer, helping to remove oxygen during the melting process and contributing to increased strength without significantly reducing ductility. Meanwhile, the phosphorus (P = 0.024%) and sulfur (S = 0.018%) content are relatively low, thus not reducing the material's ductility and fracture resistance. Both of these elements are still below the maximum limits for medium-carbon steel standards (P < 0.03% and S < 0.03%), thus categorizing the material as good quality [13].

From these results, it can be concluded that the sprocket gear material has a composition that meets the standards for medium-carbon steel type AISI 1045 or S45C, which are commonly used in vehicle transmission components. The moderate carbon content allows the formation of ferrite and pearlite phases initially, as well as martensite after rapid quenching. This composition explains the material's ability to experience a significant increase in hardness upon ice water quenching and shot peening treatments [15].

Results and Discussion of Surface Hardness Test

Hardness testing was conducted to determine the extent to which the combination of ice water quenching and varying shot peening pressures affected the surface hardness of the sprocket gear. Hardness testing is a key parameter in assessing the success of heat and mechanical treatment processes, as changes in hardness reflect the microstructural transformation and the condition of the material's surface layer after treatment. In this study, testing was conducted using the Vickers method (VHN) at several points on the sprocket gear surface treated with shot peening pressures of 5, 6, 7, and 8 bar.

The test results showed that ice water quenching followed by shot peening with varying pressures significantly affected the surface hardness. In general, there was a consistent increase in hardness with increasing air pressure. The test data are presented in Figure 1.

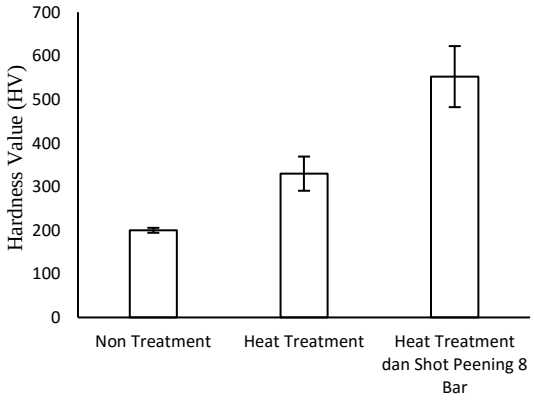


Figure 1 Graph of surface hardness of gear sprocket specimens after heat treatment, ice water quenching, and shot peening.

Figure 1 shows that the surface hardness values obtained after ice water quenching significantly increased compared to the initial condition. In the untreated condition, the surface hardness of the sprocket gear was recorded at 199 HV. After quenching using ice water, the hardness increased to 329 HV, an increase of approximately 65% compared to the initial condition. This increase indicates that rapid cooling results in microstructural changes in the form of a fine martensite phase, resulting in a harder and denser surface layer [5].

Further treatment, such as shot peening after quenching, resulted in an even more significant increase in hardness. The average hardness value reached 404 HV at 5 bar, 454 HV at 6 bar, 487 HV at 7 bar, and 552 HV at 8 bar. The highest increase occurred at 8 bar, with an increase of approximately 177% compared to the initial condition and 68% compared to the results of quenching without shot peening [12]. This improvement is due to the formation of a denser surface layer due to repeated impacts of steel shot particles, which results in local plastic deformation and compressive residual stress in the outermost layer of the material [8].

Overall, the combination of ice water quenching and shot peening has proven effective in increasing the surface hardness of medium-carbon steel sprocket gears. This combined treatment has the potential to be applied to transmission components that require high wear resistance without causing significant dimensional changes or surface defects [11].

Results and Discussion of Shot Peening Pressure Variation Hardness Test

After achieving increased hardness from the ice water quenching process, further treatment, shot peening, was performed to strengthen the surface layer through plastic deformation caused by high-speed particle impacts. This process increases the residual compressive stresses in the surface layer and results in a higher increase in hardness. Therefore, air pressure variations of 5, 6, 7, and 8 bar were used to determine the effect of impact energy on the hardening rate of the sprocket gear surface [15].

These pressure variations affect particle velocity and the depth of the layer undergoing plastic deformation [10]. Higher pressures produce greater impact energy, thereby strengthening the outer layer and progressively increasing the hardness value [12].

The results of surface hardness testing at each pressure variation are shown in Figure 2, which illustrates the relationship between increasing air pressure and changes in sprocket gear surface hardness after the combination of ice water quenching and shot peening.

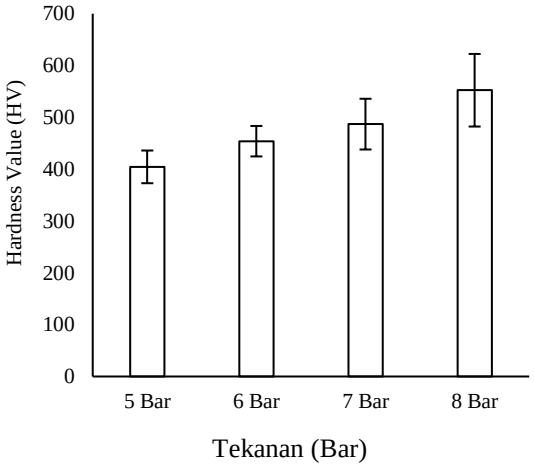


Figure 2 Surface hardness value of shot peening specimens with varying pressure

Figure 2 shows the relationship between air pressure during the shot peening process and the surface hardness of the sprocket gear after ice water quenching. It can be seen that increasing air pressure significantly increases the surface hardness of the material. The hardness value increases gradually from 404 HV at 5 bar, to 454

HV at 6 bar, 487 HV at 7 bar, and reaches 552 HV at 8 bar.

This increasing trend indicates that the higher the air pressure, the greater the impact energy of the steel shot particles hitting the specimen surface. Greater impact energy results in more intense plastic deformation in the outer layer of the material, increasing dislocation density and generating compressive residual stress, which strengthens the surface layer [16]. This compressive residual stress plays a crucial role in increasing resistance to further plastic deformation and slowing crack initiation under repeated loading [17].

The significant increase in hardness at 8 bar also indicates that the combination of the martensite structure resulting from ice water quenching and the micro-tempering effect of shot peening synergistically strengthens the surface [18]. The fine martensite layer resulting from rapid cooling forms a hard substrate, while deformation from particle impacts refines the surface grain and increases the density of crystal defects. Both of these effects contribute to a consistent increase in hardness with increasing pressure.

However, excessively high pressure increases can potentially lead to excessive residual stresses or microcracking on the material surface if not properly controlled. Therefore, selecting the optimum pressure requires a balance between hardness enhancement and surface layer stability. In this study, 8 bar showed the best results without any significant surface defects, thus being considered the optimum shot peening condition for increasing the hardness of medium-carbon steel sprocket gears.

Overall, the pattern in Figure 1 shows a linear relationship between increasing shot peening pressure and surface hardness, confirming that impact energy is the dominant factor in the surface hardening mechanism resulting from the combination of ice water quenching and shot peening.

Microstructure Observation Results and Discussion

Microstructure observations were conducted to corroborate the hardness test results and explain the mechanism of surface hardness increase resulting from the combination of ice water quenching and shot peening. The examinations were conducted on two conditions: untreated specimens and specimens treated with a combination of ice water quenching and shot peening at 8 bar pressure.

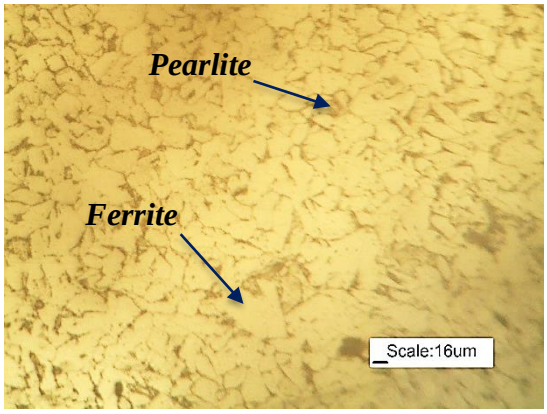


Figure 3 Microstructure of the surface of the non-treatment specimen

Figure 3 shows the microstructure of the sprocket gear before quenching and shot peening. The microstructure is dominated by two main phases: ferrite and pearlite. The ferrite phase appears lighter in color with relatively large, interconnected polygonal grains, while the pearlite phase appears darker and is distributed within the ferrite matrix in a lamellar pattern.

This ferrite-pearlite structure is characteristic of medium-carbon steel in the as-received condition, where phase transformation has not yet occurred due to heat treatment. Ferrite is soft and ductile, while pearlite, containing cementite lamellae, has higher hardness [13]. The higher proportion of ferrite results in a lower hardness, as reflected in the hardness test result of 199 HV.

The relatively coarse grain size and uneven distribution of pearlite indicate that the material has not yet undergone hardening or plastic deformation in the surface layer. Thus, this microstructural condition explains why untreated sprocket gears have lower wear resistance and hardness compared to specimens that have been quenched or shot peened.

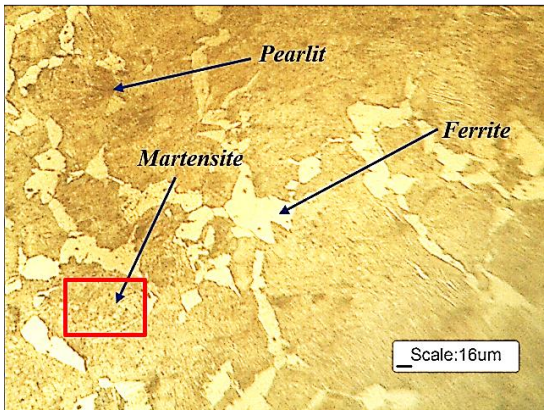


Figure 4 Microstructure of ice water quenching and 8 bar pressure shot peening specimens

Figure 4 shows significant micromorphological changes after the sprocket gear was treated with a combination of ice water quenching and shot peening. The microstructure in the image indicates the presence of three main phases: martensite, pearlite, and ferrite. The martensite phase appears as dark, needle-like regions (lath martensite) formed by rapid cooling during quenching, while lighter-colored ferrite and pearlite are still visible in some areas of the matrix [13].

These microstructural changes directly affect the increase in surface hardness. The combination of ice water quenching and 8 bar shot peening increased the hardness from 329 HV to 552 HV, approximately 68% higher than the quenched result. This increase is due to two main mechanisms: (1) the formation of fine martensite, which provides a high base hardness, and (2) plastic deformation due to shot peening, which increases dislocation density and generates compressive residual stress.

A dense martensite layer and a homogeneous deformed zone provide a hard surface and resistance to crack initiation and wear [19]. Furthermore, visual observation reveals a darker surface color and a smoother texture compared to the untreated condition, indicating increased homogeneity of the hard layer. Thus, these microstructural observations clearly justify the increase in surface hardness values obtained in the Vickers test and demonstrate that the combination of ice water quenching and shot peening effectively strengthens the outer layer of the gear sprocket without causing microdefects [12].

CONCLUSION

The combination of ice water quenching and shot peening has been shown to effectively increase the hardness and refine the microstructure of medium carbon steel gear sprockets. The ice water quenching process increased the surface hardness from 199 HV to 329 HV due to the formation of a fine martensite phase, while the shot peening treatment with varying pressures of 5–8 bar resulted in a hardness increase of up to 552 HV at 8 bar, an increase of approximately 177% compared to the initial condition. Microstructural observations revealed a fine martensite layer and a dense plastic deformation zone, indicating the formation of compressive residual stress on the material's surface. Thus, this treatment combination produces a hard, smooth, and wear-resistant surface layer without defects, potentially offering applications in automotive transmission components to increase their service life and reliability.

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