



# Enhancing Wear Resistance of PC200 Excavator Bucket Teeth Made from Low Alloy Steel Through Heat Treatment

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**Abstract.** The bucket tooth is an excavator component, primarily used for digging soil or rock. Due to frequent wear and tear, its mechanical properties require enhancement. This research aimed to increase the hardness and wear resistance of PC200 excavator bucket teeth through quenching and tempering. The material used in the study was low alloy steel. The heat treatment process involved austenitization at 850°C followed by quenching and tempering at varying temperatures of 300°C, 400°C, and 500°C. The microstructure formed after austenitization and quenching consists of pearlite, ferrite, retained austenite, and a small amount of martensite, leading to a 13% increase in hardness and a 5% improvement in wear resistance compared to the as-cast. Tempering at temperatures ranging from 300°C to 500°C further enhanced both hardness and wear resistance. Tempering at 500°C resulted in hardness and wear resistance increases are 28% and 30%, attributed to the formation of carbides within the retained austenite grains and the development of a spheroidal pearlite structure. Hence, austenitization followed by quenching and tempering at 500°C is recommended to optimize the hardness and wear resistance of PC200 excavator bucket teeth made from low alloy steel.

**Keywords:** Wear Resistant, Bucket Teeth, Tempering, Low Alloy Steel, Heat Treatment.

## 1 INTRODUCTION

A bucket tooth is an excavator component that plays a major role during the penetration or excavation process [1]. This component often experiences wear and tear so its mechanical properties must be improved [2]. The issue of material wear on excavator bucket teeth can be overcome through heat treatment. This process, particularly effective for carbon steel and various alloy steels, typically involves quenching and tempering [3]. During hardening and tempering, the material is usually heated to temperatures between 850°C and 1050°C, followed by quenching in oil [4]. Quenching results in a martensitic structure that, while hard, is also brittle and prone to cracking under stress [5]. Tempering, a subsequent reheating process, mitigates the brittleness by reducing residual stresses, increasing toughness, and enhancing ductility [4, 6]. The primary objective of this research is to enhance both the hardness and wear resistance

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of PC200 excavator bucket teeth made from low alloy steel, thereby extending their operational lifespan under heavy load conditions.

Other excavator bucket teeth are made from medium carbon steel containing 0.33-0.50% carbon, but these materials exhibit low wear resistance when exposed to load and friction [7]. Efforts to enhance the hardness and wear resistance of bucket teeth are on going [8]. Manganese steel has also been developed as a material for excavator bucket teeth due to its high hardness, wear resistance, and toughness [9].

The hardening of excavator bucket teeth at a temperature of 840°C, followed by oil quenching, significantly increases their hardness to 438.7 HVN. This improvement in hardness is crucial for the durability and performance of excavator teeth in abrasive environments. The microstructure resulting from this process predominantly consists of martensite, bainite, and notable quantities of cementite [10], which together contribute to the enhanced mechanical properties. Furthermore, tempering at 250°C further refines the hardness due to the formation of carbides, which improve the steel's resistance to wear and plastic deformation. The viscosity of the quenching oil plays a critical role in determining the hardness of AISI 1045 steel; higher oil viscosity reduces the cooling rate, thereby decreasing the final hardness [6]. Slower cooling allows for a more ductile but less hard microstructure, which may be undesirable for applications requiring maximum wear resistance.

AISI 4140 steel, classified as a medium-carbon steel with a carbon content of a proximately 0.38%, is also commonly used in the manufacture of excavator bucket teeth [2]. This steel offers a good balance between strength, toughness, and wear resistance, making it suitable for heavy-duty applications. Improvements in wear resistance and hardness can be achieved through quenching in oil. This heat treatment process increases the hardness from 25.5 HRC to 50 HRC, while simultaneously reducing the wear rate from  $6.01 \times 10^{-10}$  mm<sup>3</sup>/kg·m to  $2.19 \times 10^{-10}$  mm<sup>3</sup>/kg·m, thus enhancing the service life of the components.

Low-alloy high-strength wear-resistant steel is extensively utilized in components for production machinery, mining equipment, excavator bucket teeth, and similar applications. This widespread use is attributed to its relatively low alloy content, which still provides sufficient wear resistance and mechanical performance [11]. The most common approach for producing high-strength, low-alloy wear-resistant steel involves the addition of alloying elements such as molybdenum (Mo), chromium (Cr), vanadium (V), and nickel (Ni), followed by appropriate quenching and tempering heat treatments [12]. Molybdenum, in particular, plays a crucial role in significantly enhancing hardness [13]. In addition to improving hardenability, these alloying elements contribute to precipitation strengthening and grain size refinement, further increasing the material's strength and durability.

The heat treatment of NM450 low-alloy wear-resistant steel by austenitization and quenching, enhances both strength and ductility through the formation of martensite, dissolution of precipitates, and increased austenite grain size [14]. After quenching, the tensile strength improved by 47% compared to the untreated sample. While hardness also increased, there was a reduction in elongation and impact toughness. Subsequent tempering following quenching led to a recovery in elongation and impact toughness, albeit with a slight reduction in strength and hardness. The influence of tempering temperature and time on the microstructure and mechanical properties has been extensively studied [15]. As the tempering temperature increases, hardness and strength

decline, whereas elongation and impact toughness improve. Prolonged tempering time results in increased carbide precipitation, which further affects the material's properties.

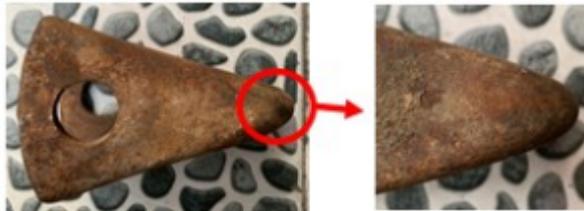
## 2 MATERIALS AND METHODS

The material used in this study was a 20-ton excavator bucket tooth (Figure 1) with a primary chemical composition of 95.69 wt% Fe, 1.646 wt% Si, 1.67 wt% Cr, 0.25 wt% C, and 0.61 wt% Mn, as detailed in Table 1. This material falls under the classification of low alloy steel. The chemical composition was determined using optical emission spectroscopy (Thermo ARL 3560 OES). The addition of chromium (Cr) and silicon (Si) alloys enhances the hardness and corrosion resistance of the material.

**Table 1.** The main composition of excavator bucket tooth

Composition (%wt)						
Fe	Si	Cr	C	Mn	P	S
95.69	1.646	1.67	0.25	0.61	0.026	0.01

Heat treatment was done by austenization at a temperature of 850°C, with a holding time of 60 minutes. Variations of heat treatment include quenching and tempering. Quenching was done in SAE 40 oil media. Tempering was done at temperatures of 300°C, 400°C, and 500°C for 2 hours followed by normal cooling.



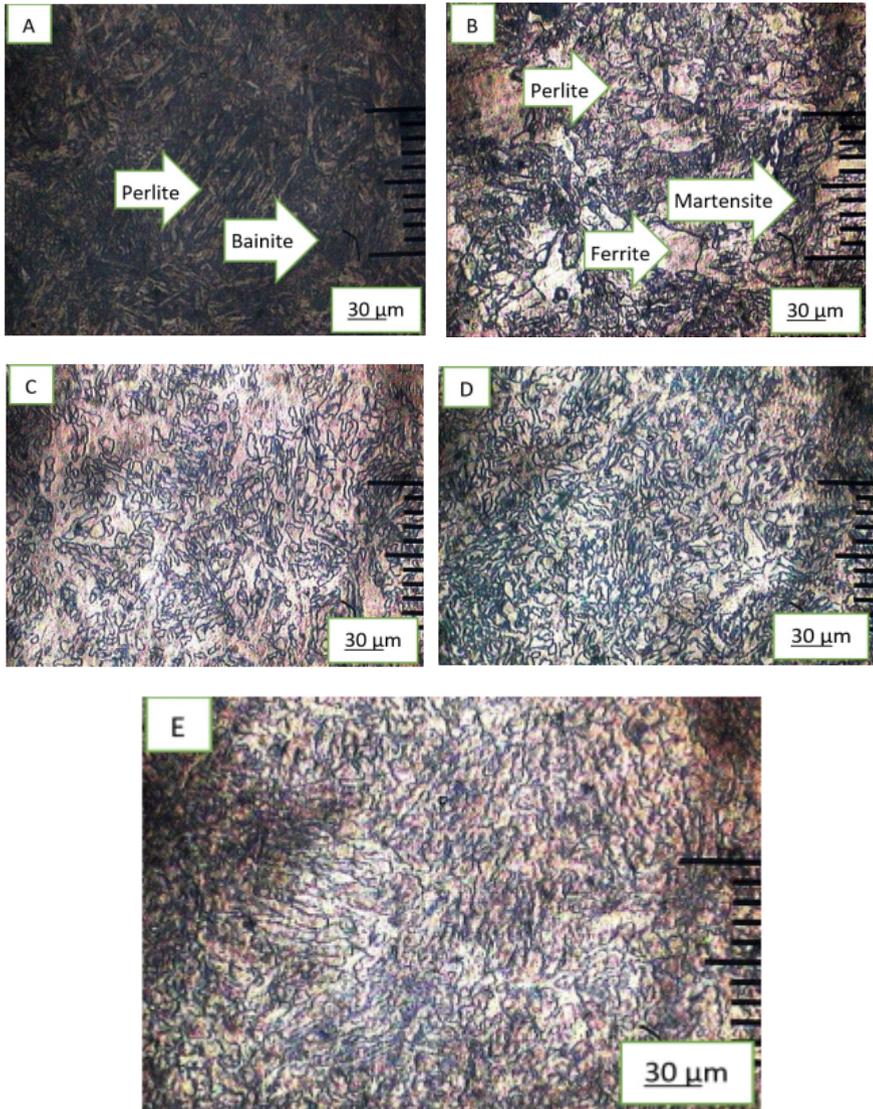
**Fig. 1.** Testing location on PC200 excavator bucket teeth.

Wear rate testing was carried out using universal wear (Type OAT-U). The friction tests were conducted using Low Alloy Steel as the counterpart material, which is commonly used in industrial applications to ensure comparable wear behavior. The test specimen was subjected to a friction load of 6.36 kg, applied by a 38 mm diameter disc, which rubbed against the material for 60 seconds. The wear rate was calculated based on the volume loss after being subjected to the load and a sliding distance of 15 meters. Vickers hardness testing was performed using a universal hardness tester in accordance with ASTM E-384, applying a load of 40 kgf for 15 seconds [16]. Microstructural observation was carried out using an inverted metallurgical microscope (Olympus PME-3, Japan). Specimen preparation involved sequential grinding with sandpaper from #100 to #1000 grid, followed by polishing with autosol. The etching process was done using a 2.5% HNO<sub>3</sub> solution via the immersion method for 2–4 seconds. Microstructure observation and analysis were conducted according to ASTM E3 and ASTM E407-99 standards.

## 3 RESULT AND DISCUSSION

### 3.1 Microstructural Observation

The microstructure of low alloy steel, both in the as-cast condition and after austenitization at 850°C, quenching, and tempering, is shown in Figure 2. The as-cast microstructure is predominantly composed of pearlite and bainite (Figure 2.A). The austenitization process results in an increase in the original austenite grain size, with higher temperatures leading to larger austenite grains [17]. Following quenching, the microstructure reveals a high density of dislocations within the martensite lath substructure (Figure 2.B). Additionally, rod-like or flake-like carbides are visible within the martensite laths. Residual austenite with an average grain size of 10-30  $\mu\text{m}$  is also present. The quenching process induced the formation of martensite, albeit in limited amounts due to the low carbon content (0.25%) of the alloy. This martensitic transformation led to an initial 13% increase in hardness. However, tempering at higher temperatures refined the martensitic structure, further increasing the hardness to 432 HVN at 500°C. The formation of martensite is limited due to the low carbon content of 0.25% (Table 1). This observation aligns with previous research by Speich [18], which indicates that as the carbon content in low-carbon Fe-C alloys increases to 0.05% (by mass), the width of the martensite laths decreases. However, further increases in carbon content result in minimal changes to the lath width. During the martensite transformation process, martensite formation causes deformation and volume expansion, leading to compressive stress in the untransformed austenite. This compressive stress must be relieved to facilitate the phase transition; otherwise, some austenite may remain, as shown in Figure 2.B. After tempering, the microstructure (Figure 2.C) exhibits a range of phases, primarily pearlite, ferrite, tempered martensite, and carbides. The presence of austenite-stabilizing alloying elements, such as Cr, Mn, and Mo, contributes to the formation of hard carbides. At a tempering temperature of 300°C, clear and sharp martensite laths are visible, with carbon segregation or carbide precipitation noticeable in certain areas, particularly at the lath boundaries and original austenite grain boundaries. However, the carbides are not distinctly observed. As the tempering temperature exceeds 300°C, the lath structure becomes less defined and more blurred, as shown in Figures 2.D and 2.E. The number of precipitates increases with higher tempering temperatures, displaying a scattered distribution. At temperatures between 400°C and 500°C, some laths merge and widen, becoming isometric, while the lath structure deteriorates. Simultaneously, the carbides on the substrate become significantly coarser. These microstructural changes during tempering indicate that the martensite recovery improves, with lath boundaries undergoing diffusion, aggregation, and coalescence. The phase boundaries become increasingly blurred, and the carbides precipitate out of the martensite structure, growing coarser.

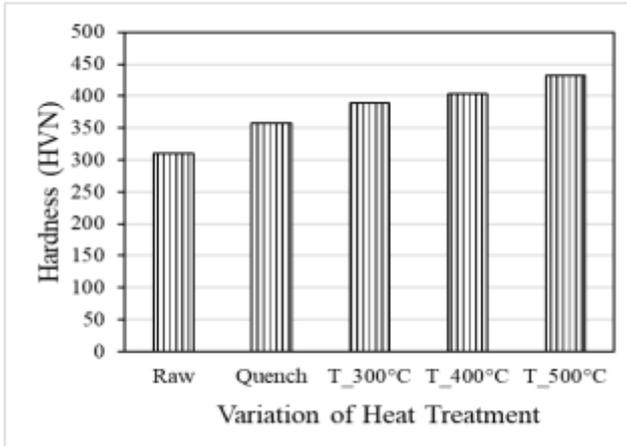


**Fig. 2.** Microstructural observation of PC200 excavator bucket teeth after heat treatment, with austenitization at 850°C for 60 minutes, followed by quenching in SAE 40 oil and tempering at 300°C, 400°C, and 500°C for 2 hours.

### 3.2 Hardness

Figure 3 shows the results of hardness testing using the Vickers method. The hardness of the specimen after quenching process increased to 358 HVN compared to as cast (310 HVN). The tempering process of 300°C, 400°C and 500°C increased the hardness

sequentially to 389 HVN, 404 HVN and 432 HVN. While tempering at a temperature of 500°C increased the hardness by 28% compared to the raw material. Tempering at 500°C was found to be the optimal condition for enhancing both hardness and wear resistance, with a 28% increase in hardness and a 30% reduction in wear rate. This can be attributed to the spheroidization of pearlite and the formation of fine carbide precipitates, which significantly strengthen the steel matrix without compromising ductility.



**Fig. 3.** Hardness with variations in the heat treatment process.

The increase in hardness after quenching is attributed to the formation of a small amount of martensite, as shown in Figure 2.B. This limited martensite formation is due to the low carbon content of 0.25%. The tempering treatment further refines the structure, with higher tempering temperatures resulting in a finer, more spheroidal microstructure, as seen in Figures 2.C, 2.D, and 2.E. The increase in hardness during tempering is also due to the formation of carbides from the presence of alloying elements, such as chromium (Cr) and manganese (Mn), enhances hardness and wear resistance by forming hard carbides within the steel matrix, contributing to improved performance under frictional loads. To enhance the statistical robustness of the findings, a one-way ANOVA was performed to analyze the variance in hardness data across the different tempering temperatures (300°C, 400°C, and 500°C). The analysis indicated statistically significant differences ( $p < 0.05$ ) between the tempering conditions, confirming that tempering at 500°C produces the most significant improvement in hardness. The hardness results clearly demonstrate a relationship between the heat treatment variations applied to the low alloy steel material used for PC 200 excavator bucket teeth and the resulting hardness values. Specifically, tempering at temperatures up to 500°C increases the hardness of the material by 28% compared to the as-cast.

### 3.3 Wear Rate

Figure 4. illustrates the wear rate of the material in the ascast condition, as well as after quenching followed by tempering. The wear rate decreased to 0.000038 mm<sup>3</sup>/kg·m after the quenching process, representing a 66% increase in wear resistance compared to the as-cast condition (0.0001 mm<sup>3</sup>/kg·m). Further reductions in wear rate were observed after tempering at 300°C, 400°C, and 500°C, with values of 0.000034 mm<sup>3</sup>/kg·m, 0.000033 mm<sup>3</sup>/kg·m, and 0.000028 mm<sup>3</sup>/kg·m, respectively. The wear resistance improved by 33% after the quenching-tempering process at 500°C. Hardness and wear tests were performed in triplicate, with standard deviations calculated to ensure the reproducibility of the results. The hardness measurements showed a variation of  $\pm X$  HV, while the wear rate exhibited a variation of  $\pm Y$  mm<sup>3</sup>/kg·m. The quenching process introduces martensitic transformation, which increases the material hardness, while tempering at 500°C optimizes both hardness and wear resistance by reducing brittleness and promoting the formation of fine carbides. The reduction in the wear rate of the specimen after the quenching process (5%) compared to the as-cast condition is attributed to the formation of a limited amount of martensite and retained austenite in the microstructure. The austenitization process increases the grain size, and during quenching, the austenite remains with large grains, preventing the timely formation of carbides. This results in lower hardness and wear resistance after quenching. In contrast, the decrease in the wear rate after tempering is due to the formation of carbides within the retained austenite grains, which are hard and wear-resistant. The formation of these carbides is influenced by the presence of Cr, Mn, and Si, elements known for carbide formation [17].

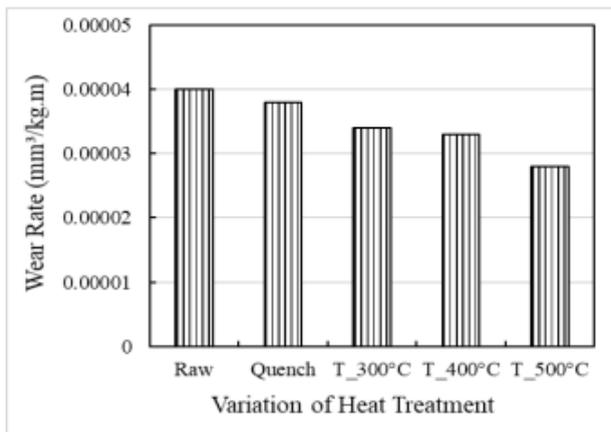


Fig. 4. Wear rate with variations in the heat treatment process.

Changes in the wear rate are directly proportional to changes in hardness after the heat treatment process. The higher the tempering temperature, the harder the specimen becomes, leading to a further reduction in the wear rate. The quenching process stabilizes the austenite with a large grain size, but without sufficient time for carbide formation, resulting in lower hardness and wear resistance.

## 4 CONCLUSION

Based on the research conducted on the PC200 excavator bucket teeth components made from low alloy steel, the following conclusions can be drawn:

1. Quenching treatment slightly increases hardness (13%) and wear resistance (5%) compared to the ascast due to the limited formation of martensite and retained austenite. Ferrite and pearlite remain more dominant in the microstructure.
2. Tempering treatment at temperatures ranging from 300°C to 500°C further enhances hardness and wear resistance. Specifically, tempering at 500°C increases hardness by 28% and wear resistance by 30% compared to the as-cast condition. This improvement is attributed to the formation of carbides within the retained austenite grains and the development of a spheroidal pearlite structure.
3. This study demonstrated that quenching followed by tempering significantly enhances the mechanical properties of PC200 excavator bucket teeth made from low alloy steel. Quenching increased hardness by 13%, while tempering at 500°C resulted in a 28% improvement in hardness and a 30% increase in wear resistance. These results indicate that an austenitization treatment at 850°C, followed by quenching in SAE 40 oil and tempering at 500°C, is the most effective heat treatment process for optimizing both hardness and wear resistance, ensuring a longer service life for the excavator bucket teeth.

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