Improving Wear Resistance of Manganese Steel for Excavator Bucket Teeth

Alvano Okie Febriananda[1], Lilik Dwi Setyana[1,*], Nugroho Santoso[1], Diyanah Hanif[1], Robith Fuadi[1], and Ahmad Muhsin Al Mataromi[1]

[1] Vocational College, Universitas Gadjah Mada, Yogyakarta, Indonesia

Corresponding author's email: lilikdwi_s@ugm.ac.id

Abstract. Bucket teeth on excavators are essential components used for digging and loading materials. Consequently, the material used must possess high wear resistance, hardness, and toughness. Manganese steel is commonly used for this purpose because of its exceptional wear resistance. This research aims to enhance the wear resistance of bucket teeth through heat treatment. The material used in this study was manganese steel containing 16.86%wt Mn. Various heat treatment including austenitization at a temperature of 1050°C followed by quenching, tempering, normalizing, and annealing. The tests conducted included Vickers hardness, wear rate, and microstructure observation using a metallurgical microscope. The annealing increases hardness by up to 33% and wear resistance by up to 50% compared to the as-cast condition, due to the formation of manganese carbides at the grain boundaries. The quenching decreases hardness and wear resistance by up to 27% and 66% compared to the as-cast condition, attributed to the formation of a stable austenite structure with a grain size of 60-80 μm. The tempering and normalizing do not increase hardness or wear resistance compared to the as-cast condition. Therefore, the annealing is recommended to improve the mechanical properties of manganese steel as a material for excavator bucket teeth.

Keywords: Manganesse Steel, Bucket Teeth, Annealing, Wear Resistant, Heat Treatment.

1   INTRODUCTION

Excavator bucket teeth are specifically designed for digging and loading materials but are frequently subjected to significant wear or breakage due to high impact loads and friction. Consequently, the material used for bucket teeth must possess high wear resistance, hardness, and toughness [1]. Traditionally, bucket teeth are made from medium carbon steel containing 0.33-0.50% carbon. However, this material tends to wear out quickly under load and friction [2]. Efforts to enhance the wear resistance and mechanical properties of bucket teeth are ongoing [3]. 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. During hardening and tempering, the material is usually heated to temperatures between 850°C and 1050°C, followed by quenching in oil. Quenching results in a martensitic structure that, while hard, is also brittle and prone to cracking under stress [4].

Manganese steel has been developed as an alternative material for excavator bucket teeth due to its superior wear resistance, hardness, and ductility [5]. These manganese steel bucket teeth are typically produced through a casting process [6]. Manganese steel is an alloy containing 10% to 15% Mn and 1% to 1.4% C. This steel is characterized by its hardness and wear resistance. However, the presence of $(FeMn)_3C$ carbides at the grain boundaries can lead to a reduction in toughness. In the as-cast condition, manganese steel contains $(FeMn)_3C$ carbides within the austenite phase [7]. Manganese in the alloy is used to stabilize austenite at room temperature [5].

Manganese steel is often used in excavator bucket teeth due to its high toughness and wear resistance. This strength is essential to handle the high impact and abrasive conditions encountered during excavation work. The high manganese content (10-15% Mn) promotes the formation of a fully austenitic structure, which enhances work hardening. This property allows the surface of the steel to harden under impact, while maintaining a strong and ductile interior, significantly improving its wear resistance.

Improvement of wear resistance and mechanical properties of bucket teeth utilizing heat treatment of manganese steel. The mechanical properties of manganese steel can be enhanced through heat treatment to achieve a fully austenitic (FCC) phase, which is stable, soft, ductile, and easily formed [8]. Manganese steel contains carbides, austenite, and a small amount of pearlite in its microstructure. Heat treatment improves its mechanical properties according to specific requirements. Previous research conducted by [5] demonstrated that quenching manganese steel (with 12% Mn) at an austenitizing temperature of 1100°C increases hardness and impact strength.

The issue of austenite dominance in the microstructure can be addressed by performing austenitizing heat treatment at 1050°C, followed by quenching, tempering, or normalizing. Manganese carbide (Mn_7C_3) forms in the annealed specimens of AISI 3401 material when austenitized at 950°C. Silicon carbide (SiC) is present in tempered specimens at 200°C, 500°C, and 700°C, appearing in nodular and intergranular forms within a ferrite matrix [9]. Hardness test results indicate a decrease in hardness with increasing tempering temperature. The improvement in hardness and wear resistance of austenitic manganese steel is attributed to high dislocation density and stacking faults, combined with high austenite stability [10]. The microstructure of manganese steel shows austenite grains ranging from 10 to 17 μm when solution heat treatment is conducted at temperatures up to 1000°C. However, the grain size increases to 50 μm when the solution heat treatment is performed at temperatures above 1000°C [11].

The addition of manganese content in manganese steel, ranging from 1.65% to 1.90%, enhances both tensile strength and hardness [12]. Manganese steel is known for its impact resistance, ductility, and wear resistance [13], as well as its high strain capacity [14]. Its wear resistance is superior to that of wrought alloy steels, cast alloy steels, stainless steels, tool steels, and high-chromium white irons [15].

The hardening process of excavator bucket teeth at a temperature of 840°C, followed by oil quenching, can increase hardness to 438.7 HVN. The resulting microstructure primarily consists of martensite, bainite, and cementite in significant amounts [4]. The tempering process at 250°C further increases hardness due to the formation of carbides. The viscosity of the quenching oil affects the hardness of AISI 1045 steel; higher viscosity leads to a lower cooling rate, resulting in reduced hardness [16]. One of the materials used as excavator bucket teeth is AISI 4140 steel [1], including the classification of medium carbon steel with a carbon element composition of around

0.38%. Enhancing wear resistance and hardness can be achieved through quenching in oil media. This process increases the hardness from 25.5 HRC to 50 HRC, while the wear rate decreases from 6.01 x 10^{-10} mm³/kg.m to 2.19 x 10^{-10} mm³/kg.m.

2   MATERIALS AND METHODS

The material used has a main chemical composition of 79.10 wt% Fe, 16.86 wt% Mn, 1.45 wt% C, and 1.29 wt% Si, as detailed in Table 1. This material is classified as Grade-A in the ASTM A128/A128M-19 standard for high manganese steel investment casting. The chemical composition was determined using optical emission spectroscopy (Thermo ARL 3560 OES).

Table 1. Composition of manganese steel

Composition (%wt)						
Fe	Mn	C	Si	Cr	P	S
79.10	16.85	1.45	1.29	1.07	0.03	0.01

Heat treatment is carried out by austenitization at a temperature of 1050°C, with a holding time of 60 minutes. Variations of heat treatment include quenching, tempering, normalizing, and annealing. In the annealing process, the slow cooling rate allows for the formation of continuous Mn_7C_3 carbides at the grain boundaries, significantly enhancing hardness and wear resistance. On the other hand, normalizing promotes the formation of non-continuous carbides, resulting in a moderate increase in hardness, though not as pronounced as in annealing. Meanwhile, tempering reduces hardness due to the precipitation of carbides and changes in the austenitic matrix, producing a softer, more ductile material.

The number of samples used in each treatment is 3, and each test is carried out 3 times to ensure data accuracy. Quenching is carried out in SAE 40 oil media, while tempering is carried out at a temperature of 300oC for 3 hours. The normalizing process is cooled in room air media, while annealing is cooled in a furnace for 48 hours.
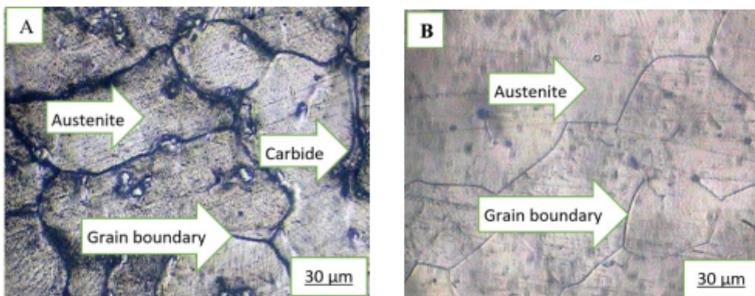
Wear testing was conducted using a universal wear testing machine (Type OAT-U). The test material was given a friction load of 6.36 kg from a 38 mm diameter rotating disc for 60 seconds. The wear rate was calculated based on the volume lost after being rubbed with a certain loading and distance. Hardness testing was conducted using a universal hardness tester with the Vickers method (ASTM E-384) with a loading of 40 kgf for 15 seconds. Impact testing used an impact tester (Controlab) with an initial energy of 300 J. Microstructure observation used a metallurgical microscope with inverted (Olympus PME-3, Japan). Specimen preparation was carried out by grinding with sandpaper #100 to #1500 followed by polishing with autosol. The etching process was carried out with 2.5% concentration HNO3 liquid using the immersion method for 3-5 seconds.

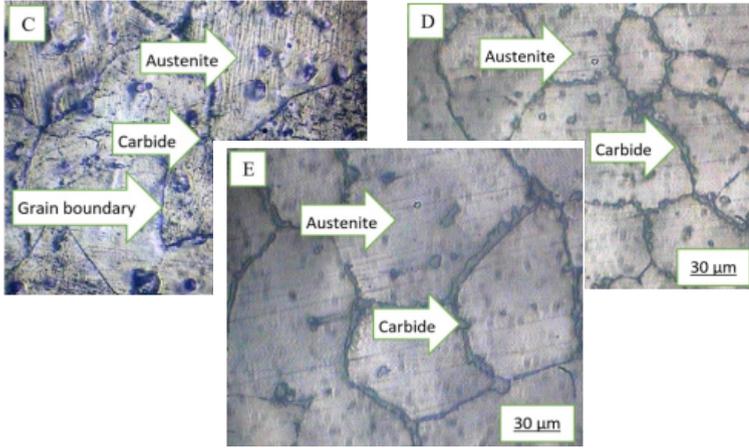# 3 RESULT AND DISCUSSION

3.1 Microstructural Observation

Figure 1 illustrates the microstructure of manganese steel with 16.85 wt% Mn content in both the as-cast state (A) and after undergoing various heat treatments, including quenching (B), tempering (C), normalizing (D), and annealing (E). The as-cast microstructure is predominantly composed of the austenite phase with minimal carbide presence at the grain boundaries. Quenching rapidly cools the steel, leading to the formation of a coarse austenitic microstructure without significant carbide precipitation. This microstructure reduces both hardness and wear resistance, as the lack of carbides diminishes the material's ability to resist abrasive forces. The austenite grains are large and unreinforced, resulting in lower wear resistance compared to annealed or normalized conditions. Austenitization at 1050°C followed by quenching in oil results in a stable austenite structure, with no carbides forming at the grain boundaries. Tempering leads to the formation of carbides at the grain boundaries, which is evidenced by the increased grain boundary size. The normalizing and annealing treatments yield a microstructure consisting of both continuous and non-continuous carbides at the grain boundaries, along with the austenite phase. Extended cooling times allow for the formation of a greater quantity of stable carbides. Microstructural observations reveal that these carbides tend to be distributed along the austenite grain boundaries. The heating process, followed by rapid cooling, results in a reduction of both continuous and non-continuous carbide precipitation at the grain boundaries. The carbides formed are Mn_7C_3, which are known for their hardness and wear resistance. The increase in hardness and wear resistance is attributed to higher dislocation density and stacking faults, coupled with enhanced austenite stability [9].

Microstructural observations reveal a variation in carbide size, ranging from 2 to 10 μm, depending on the heat treatment applied. Non-continuous carbides at the grain boundaries tend to be larger with slower cooling rates. Annealing treatment promotes the formation of more extensive carbides that coalesce within the austenitic matrix. In contrast, the quenching treatment results in a reduction in grain boundary size and carbide precipitation, leading to decreased hardness and wear resistance. Normalizing treatment, however, results in the formation of non-continuous carbides within the austenite matrix, which enhances both hardness and wear resistance.
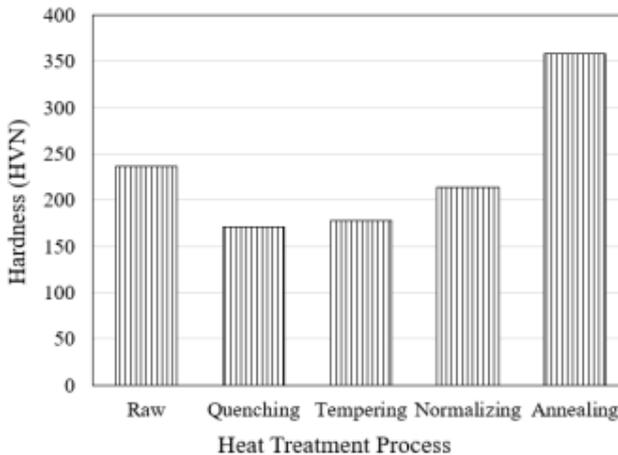
Fig. 1. Micro structure observation on manganese steel with variation of heat treatment.

3.2   Hardness

Figure 2 presents the results of hardness testing using the Vickers method. The hardness value of the as cast is 237 HVN. While the hardness after austenization followed by quenching, tempering, normalizing and annealing processes are 171, 178, 214 and 358 HVN respectively. After the quenching process, the hardness of the specimen decreased to 171 HVN, compared to 237 HVN for the as-cast raw material. The normalizing process reduced the hardness to 214 HVN, representing a 9% decrease compared to the as-cast hardness. In contrast, the annealing treatment increased the hardness to 358 HVN, reflecting a 33% increase relative to the as-cast material.

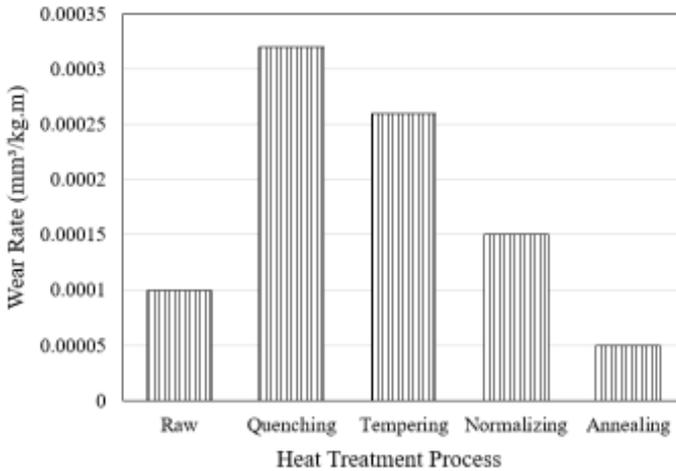**Fig.2.** Hardness with variations in heat treatment process.

The reduction in hardness by up to 27% during the quenching process is attributed to the microstructure being dominated by austenite, without the presence of carbides at the grain boundaries (Figure 1). The rate of cooling during heat treatment has a direct influence on carbide formation. Slower cooling rates, such as in annealing, provide sufficient time for Mn_7C_3 carbides to form and grow, especially at grain boundaries, leading to increased hardness and wear resistance. In contrast, rapid cooling, as seen in quenching, prevents carbide formation, resulting in a softer austenitic structure with lower mechanical properties.

The grain size of austenite plays a critical role in determining the hardness and wear resistance of manganese steel. After various heat treatments, smaller austenite grains, typically formed during annealing, contribute to higher hardness due to the increased density of grain boundaries, which impede dislocation movement. Larger grains, such as those formed after quenching, reduce hardness and wear resistance as the material becomes more susceptible to plastic deformation and wear. Normalizing treatment has produced little carbides at the grain boundaries so that it only slightly reduces the hardness compared to the raw material. Annealing treatment increases the hardness significantly (33%) compared to the raw material because slow cooling has caused the formation of continuous carbides and non-continuous carbides in sufficient quantities at the grain boundaries (Figure 1).

Manganese carbides (Mn_7C_3) play a crucial role in improving the mechanical properties of manganese steel, particularly after annealing treatment. These carbides form at the grain boundaries and within the austenitic matrix, providing hard phases that resist deformation. The presence of Mn_7C_3 carbides increases both hardness and wear resistance by inhibiting grain boundary movement and reinforcing the austenite matrix, making the material more resistant to wear under abrasive conditions.

3.3　Wear Rate

Figure 3 illustrates the results of the wear rate test for both the as-cast material and those subjected to various heat treatments. The wear rate on the cast as-cast is 0.0001 mm³/kg.m, while the wear rate after the austenitization process followed by quenching, tempering, normalizing and annealing are 0.0003, 0.0002, 0.00014 and 0.00005 mm³/kg.m respectively. The wear rate increased to 0.0003 mm³/kg·m (a 66% increase) after the quenching process, compared to 0.0001 mm³/kg·m for the as-cast material. After tempering, the wear rate decreased by 33% relative to the rate observed after quenching. Normalizing treatment did not reduce the wear rate compared to the as-cast condition. In contrast, the annealing treatment significantly reduced the wear rate to 0.00005 mm³/kg·m, representing a 50% decrease compared to the as-cast material.

Fig.3. Wear rate with variations in the heat treatment process.

The increase in the wear rate on the specimen after the quenching process is caused by the microstructure being dominated by soft austenite. While the decrease in the wear rate on the specimen after the annealing process is caused by the formation of (Mn_7C_3) carbides at the grain boundaries and inside the hard and wear-resistant austenite grains. The change in the wear rate is directly proportional to the change in the hardness value after the heat treatment process. The slower the cooling rate of the specimen, the harder it is so that the wear rate decreases, conversely the faster the cooling, the harder the hardness decreases and causes the wear rate to increase.

The annealing treatment of manganese steel successfully increased wear resistance by 50% and increased hardness by 33% compared to as cast. The increase was due to the growth of manganese carbide (Mn_7C_3)) at the grain boundaries (continuous carbides) and in the austenite grains (noncontinuous carbides). The annealing treatment at temperatures above 1000°C caused the austenite grain size to increase by [10]. The quenching treatment made the austenite stable with a large grain size and did not have time to form carbides. This caused the hardness and wear resistance after quenching to be low.

The phase formed and the grain boundary size of the microstructure after heat treatment determine the mechanical properties of the material, especially hardness and wear resistance. The slower the cooling rate will provide an opportunity for the formation of Mn_7C_3) carbides which are hard and wear resistant. The amount of carbide will be more formed if the cooling is slower, this can be seen from the microstructure of the normalizing and annealing specimens.

Heat treatment changes the austenite grain size which determines the hardness and wear resistance of manganese steel. The austenite grain size after quenching is 100-150 μm (Figure 1.B), which causes the hardness and wear resistance to decrease compared to as cast. The austenite grain size increases during austenization at a temperature of 1050°C. Rapid cooling causes the formation of stable austenite without the formation of carbides so that the hardness is low. Tempering treatment at a temperature of 300°C

provides an opportunity for carbide growth at the grain boundaries (Figure 1.C) in small amounts which increases hardness and wear resistance. Normalizing treatment successfully forms carbides at the grain boundaries which increases hardness and wear resistance compared to as cast (Figure 1.D). The increase in hardness and wear resistance is up to 9% and 28% compared to as cast. The average austenite grain size formed is around 70-90 μm. Normalizing treatment with slow cooling rate has given opportunity to form manganese carbide (Mn7C3).

Annealing treatment with very slow cooling rate has given opportunity to form manganese carbide on grain boundary in large amount. It can be seen that grain boundary looks thick and very clear. Carbide has made wear resistance increased. Increased hardness and wear resistance reached 33% and 50% compared to as cast. Austenite grain size ranges from 60-90 μm (Figure 1.E).

4   CONCLUSION

Based on the conducted research, the following conclusions can be drawn:
1. Annealing treatment increases hardness by 33% and wear resistance by 50% compared to as-cast condition. This increase is due to the formation of manganese carbides (Mn_7C_3) which are continuously distributed along the grain boundaries
2. Quenching reduces hardness by up to 27% and wear resistance by up to 66% compared to the as-cast condition. This reduction is due to the formation of a stable austenite structure with a grain size of 60- 80 μm. Neither tempering nor normalizing treatments enhance hardness or wear resistance compared to the as-cast state.
3. Based on the observed hardness and wear rate values, annealing heat treatment is recommended to enhance the physical and mechanical properties of manganese steel for use in excavator bucket teeth.

REFERENCES

1. S. H. Suryo, A. P. Bayuseno, J. Jamari, and A. I. Wahyudi, "Analysis of Rake Angle Effect to Stress Distribution on Excavator Bucket Teeth Using Finite Element Method," Civil Engineering Journal, vol. 3, no. 12, p. 1222, Dec. 2018
2. A. P. Bayuseno and D. A. Negoro, "Peningkatan Nilai Kekerasan pada Bucket Teeth Excavator dengan Metode Pack Carburizing dan Media Quenching Oli SAE 20W-50 serta Cangkang Kerang sebagai Energizer," Rotasi, vol. 20, no. 4, p. 195, 2019
3. I. Azmy, "Studi pengaruh proses tempering terhadap struktur mikro dan kekerasan postannealing baja mangan austenitik," Jurnal Polimesin, vol. 19, p. 170, 2021
4. P. Fernandes and K. N. Prabhu, "Effect of Section Size and Agitation on Heat Transfer During Quenching of AISI 1040 Steel," Journal of Materials Processing Technology, vol. 183, no. 1, pp. 1–5, 2007. Available at: https://doi.org/10.1016/j.jmatprotec.2006.08.028

5. B. Bandanadjaja and E. Hidayat, "The effect of two-step solution heat treatment on the impact properties of Hadfield austenitic manganese steel," Journal of Physics: Conference Series, vol. 1450, no. 1, 2020.

6. B. Tarigan, "Karakterisasi Material Bucket Teeth pada Excavator," presented at Seminar Nasional Teknik Mesin, 2016

7. A. K. Srivastava and K. Das, "Microstructural characterization of Hadfield austenitic manganese steel," Journal of Materials Science, vol. 43, no. 16, pp. 5654–5658, Aug. 2008

8. S. Alyas, Effect of Heat Treatment and Chemical Composition on Microstructure and Mechanical Properties of Hadfield Steels, M.S. thesis, Middle East Technical University, 2003

9. C. Hussen and Sadino, "Pengaruh Variasi Temperatur Tempering Terhadap Sifat Mekanik dan Struktur Mikro pada Baja Mangan Hadfield AISI 3401 Hammer Clinker Cooler PT Semen Gresik," Jurnal Teknik POMITS, vol. 1, no. 1, 2012

10. Z. M. Huo, J. Qichuan, F. Shaobo, and X. Jingpei, "Improved Work Hardening Ability and Wear Resistance of Manganese Steel Under Non-Severe Impact Loading Conditions," Materials Engineering, 2003

11. L. A. Dobrzanski, A. Grajcar, and B. Borek, "Influence of hot working conditions on a structure of high manganese austenite steel," Journal of Hot-Deformed Austenite Steels, Materials Engineering, pp. 795–798, 2008

12. T. V. Rajan, S. Sharman, and A. Sharma, Heat Treatment Principles and Techniques, 3rd ed., New Delhi, India: Prentice Hall of India Pvt. Ltd., 1997

13. E. R. Hall, "Technical Report No. C6-17.1," ASM International, p. 15, 1996

14. Y. N. Dastur and W. C. Leslie, "Mechanism of Work Hardening in Hadfield Manganese Steel," Metallurgical Transactions A, vol. 12A, p. 749, 1981

15. H. R. Clauser, Industrial and Engineering Materials, New York, NY: McGraw-Hill, 1975.

16. H. Hariningsih, T. Daryanto, and L. Lutiyatmi, "Pengaruh Variasi Media Quenching dan Tempering terhadap Struktur Mikro dan Kekerasan Baja AISI 1045," Creative Research in Engineering, vol. 2, no. 2, p. 52, 2022. Available at: https://doi.org/10.30595/cerie.v2i2.14317