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Increased Hardness Value of Medium Manganese Steel Through Double Tempering, Hot Rolling, and Variation of Cooling Media

Arif Tjahjono[1], Firly Giska Pramesti[1], Nadya Salsabila Frendyta[1]
Permana Andi Paristiawan[2]
[1]Department of Physics, Faculty of Science and Technology, Syarif Hidayatullah State Islamic University Jakarta, Banten,15412, Indonesia
[2]Research Center for Metallurgy, National Research and Innovation Agency (BRIN), Banten, 15314, Indonesia

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Corresponding Author:

Arif Tjahjono,
Email: arif.tjahjono@uinjkt.ac.id

ABSTRACT

Research has been conducted to enhance the hardness value of medium manganese steel through a heat treatment. Initially, this process begins with austenization at a temperature of 900°C, followed by tempering at 650°C and double tempering at 600°C, with each stage lasting 30 minutes. Subsequently, each stage concludes with a hot rolling process, after which air or water cools the material. As a result of these processes, the hardness tests revealed an increase in the hardness of medium manganese steel, reaching up to 389.70 BHN with a tensile strength of 827 MPa, which was notably achieved through air cooling. This significant increase in hardness is attributed to the emergence of the martensite phase and the presence of a large number of carbides, which are more evenly distributed after the double-tempering process. Additionally, small amounts of carbides were observed in the austenite matrix. Upon examination of the SEM fractography results, it was revealed that the fracture was mixed, with a cleavage area slightly larger than the dimple area. This observation suggests that despite its high hardness value, the sample retains good toughness.

1. INTRODUCTION

The rapid advancement in the field of medium manganese steel is currently garnering significant attention due to its widespread applications. These applications span various industries, including mineral processing, mining, and transportation. This versatile material has thus become a focal point in contemporary material science research (Azmy & Saragih, 2020). Medium manganese steel, also recognized as austenitic manganese steel, is a unique material primarily composed of 10 – 14% manganese and 0.7 – 1.4 % carbon, as per the specifications of ASTM A-128-64 (Tęcza & Sobula, 2014). This steel is renowned for its exceptional impact strength, wear resistance, and high hardness value (Hance, 2018; Kang et al., 2018). However, its application often encounters challenges due to its failure under continuous loading (Azmy et al., 2021), which subsequently reduces the strength of medium manganese steel, particularly its hardness value. Therefore, it is imperative to devise strategies to address this issue and enhance the performance of this widely used material.

Numerous studies have been undertaken to enhance the strength of medium manganese steel. For instance, research by (Azmy et al., 2021) investigated the impact of the tempering process on the microstructure formation of austenitic manganese steel. Their findings revealed that after tempering at 400°C, austenitic manganese steel exhibited a lower hardness value, forming twin martensite and a coarse-grained carbide phase ($FeMn_3C$) in its austenite matrix. In another study, Frendyta et al. (2023) demonstrated that a solution treatment process at 1100°C for 30 minutes successfully increased the toughness of austenite manganese steel, albeit at the expense of a decrease in hardness from an initial 254 HB to 198.2 HB with ice water cooling. Further research by Paristiawan et al. (2021) emphasized the significant influence of cooling media on the hardness value of the produced manganese steel, highlighting the importance of variations in cooling media. Another potential treatment process is hot rolling, which has been shown to increase the strength of medium manganese steel. Research by Liu et al. (2020) indicated that hot rolling resulted in a structure with neater and finer grains, imparting ductile properties to the material. The hot rolling process also led to tougher and stronger steel due to more homogeneous grain size (Okechukwu et al., 2017). These studies underscore that while much of the treatment of medium manganese steel has been focused on enhancing its toughness, there is a critical need for research to increase its hardness value.

This study aims to enhance the hardness of medium manganese steel through a series of heat treatment processes. Initially, the process begins with austenization at 900°C, a temperature selected to dissolve carbide and improve toughness (Hidayat & Bandanadjaja, 2018); it is followed by tempering at 650°C, which further decomposes the carbide and double tempering at 600°C. Each process lasts 30 minutes and allows for an even distribution of carbon, thereby increasing the hardness of the material (Bandanadjaja & Idamayanti, 2020). Subsequently, each stage concludes with a hot-rolling process. This process is designed to form grains free from residual stress, reduce defects in casting products, and enhance the mechanical properties of medium manganese steel (Paristiawan et al., 2020). In addition to these processes, variations in cooling media, specifically air and water, are also explored to determine their impact on hardness (Paristiawan et al., 2021). Through the comprehensive procedure, the hardness value of medium manganese steel is expected to increase so that the form of losses caused by continuous loading that results in a decrease in hardness value can be avoided.

2. METHOD

2.1 Tools and Materials

This study employs a variety of tools and materials to conduct the research. The tools include plasma cutting, digital callipers, table grinding machines, hand grinding machines, heat treatment furnaces (Naberthem brand, type LH-15/14"/C440), metal rolling machines, wirecut machines, mounting moulds, Buehler grinding machines (Ecomet V), Metkon Gripo 2V Polishing machine, a magnetic stirrer, an Olympus U-MSSP4 microscope, a Brinell Affri machine, a Tinius Olsen 300SL machine, and a JEOL JSM 6390A SEM machine. The material under investigation in this research is medium manganese steel, crafted to 9.9 cm × 1.62 cm × 5.56 mm. Additional materials used in the process include sandpaper with a grid of 120 to 1500, resin, catalyst, water, velvet cloth, alumina, nitric acid (HNO_3), methanol (CH_3OH), a 2% Nital solution, and 96% technical ethanol. The specific composition of the medium manganese steel used in this study is detailed in Table 1.

Table 1 Medium Manganese Steel Composition

Element	Mn	Si	S	C	P	Fe
Wt.%	13	0.4	0.03	1.15	0.045	Bal.

2.2 Methods

As illustrated in Figure 1, the study explores the intricate stages of the double tempering process, hot rolling, and the subsequent variations introduced by different cooling mediums. The primary objective of this heat treatment procedure is to investigate its influence on the hardness value and the microstructural characteristics of medium manganese steel. This investigation is pivotal in understanding the material's behavior under various conditions.

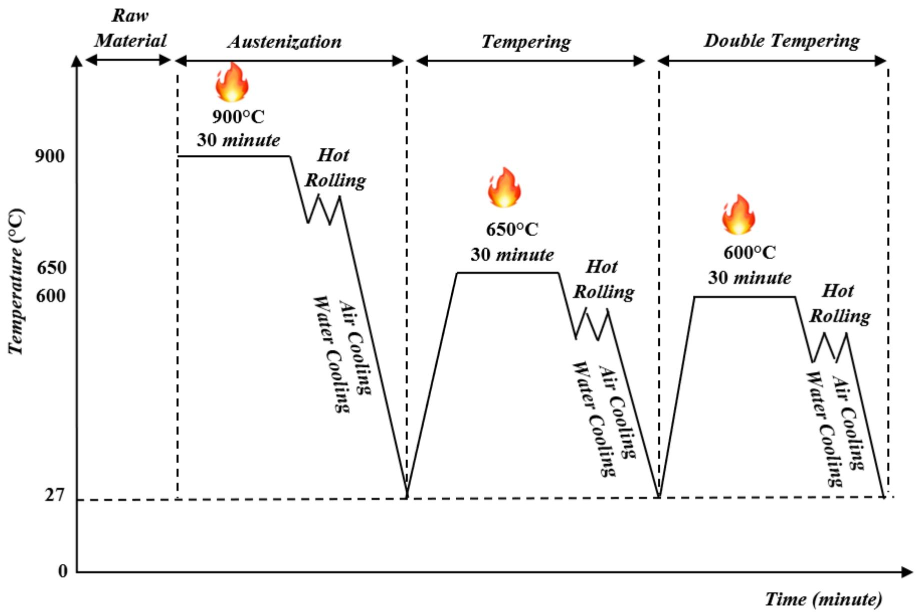

Figure 1 Double tempering, hot rolling, and variations of cooling media.

The specimens were subjected to a three-stage heat treatment in this study. The initial stage involved the austenization process, where the specimens were heated from ambient temperature to 900°C and maintained for 30 minutes, followed by hot rolling. Subsequently, the tempering process was initiated at 650°C with a holding time of 30 minutes, again followed by hot rolling. The final stage encompassed double tempering at a temperature of 600°C with a holding time of 30 minutes, succeeded by hot rolling. Each heat treatment stage concluded with cooling using air or water as the cooling media. This rigorous methodology ensures a comprehensive understanding of the material's behavior under varying conditions.

3. RESULTS AND DISCUSSION

3.1 Hardness Testing

The Brinell hardness test was meticulously conducted five times at various points on each specimen, with the mean value subsequently calculated. The testing apparatus employed was an Affri 206 RTD-type machine of Italian origin. The indenter, a steel ball with a diameter of 2.5 mm, was subjected to a load of 187.5 kg (Ridlo et al., 2020). The average hardness values obtained for each specimen are presented in Figure 2.

The hardness test results reveal that the double tempering process and the hot rolling process significantly enhanced the hardness of medium manganese steel. The hardness escalated from an initial 253 BHN to 389.70 BHN with air cooling and 362.36 BHN with water cooling. This enhancement can be attributed to the double tempering process, which facilitates a more uniform distribution of carbon (Bandanadjaja & Idamayanti, 2020), a key element known to augment the hardness of medium manganese steel. The even distribution of carbon can be seen from the metallographic results, as in Figure 4, with more carbide and martensite phases formed after the double tempering process. The carbide phase contains iron and carbon ($FeMn_3C$), while the martensite phase occurs due to delayed carbon transformation. A comparison of the cooling media, air and water, indicates that air cooling yields a higher hardness value than water cooling, as illustrated in Figure 2. This discrepancy arises from the relatively rapid and varying temperature changes between samples and cooling media (Lambang & Tamjidillah, 2020). The water used as the cooling medium in this research has a temperature of 24°C.

Water can conduct heat faster than air because the distance between water molecules is closer than the distance between air molecules. It causes the cooling rate of air to be slower than that of water. Consequently, a slower cooling process results in a more rigid and stronger structure (Priadi et al., 2017).

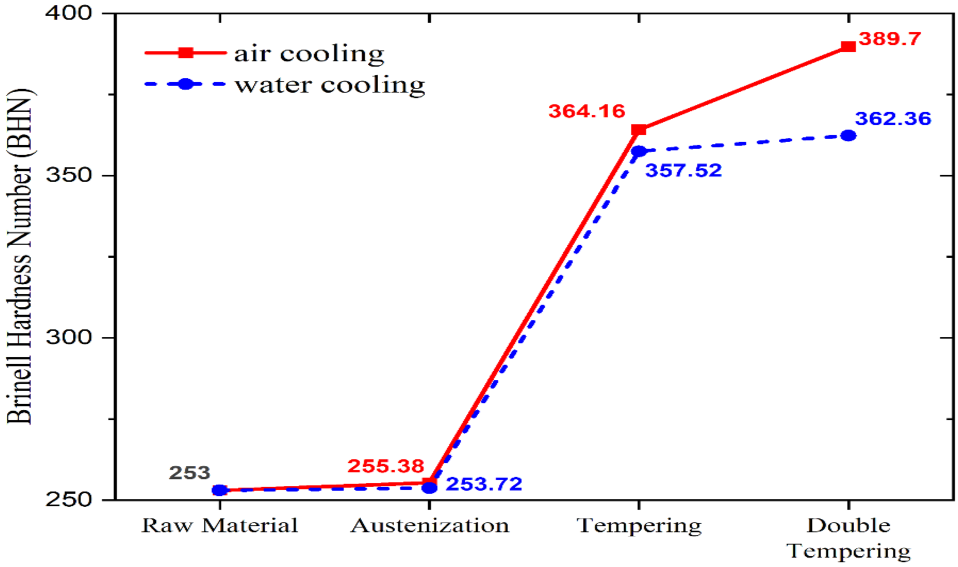

Figure 2 Results of the Brinell hardness testing.

3.2 Tensile Strength Testing

Tensile strength testing was carried out using a Tinius Olsen 300SL tensile testing machine. Tensile Test is a method used to test the tensile strength of a material by providing static loads. The results are shown in Figure 3.

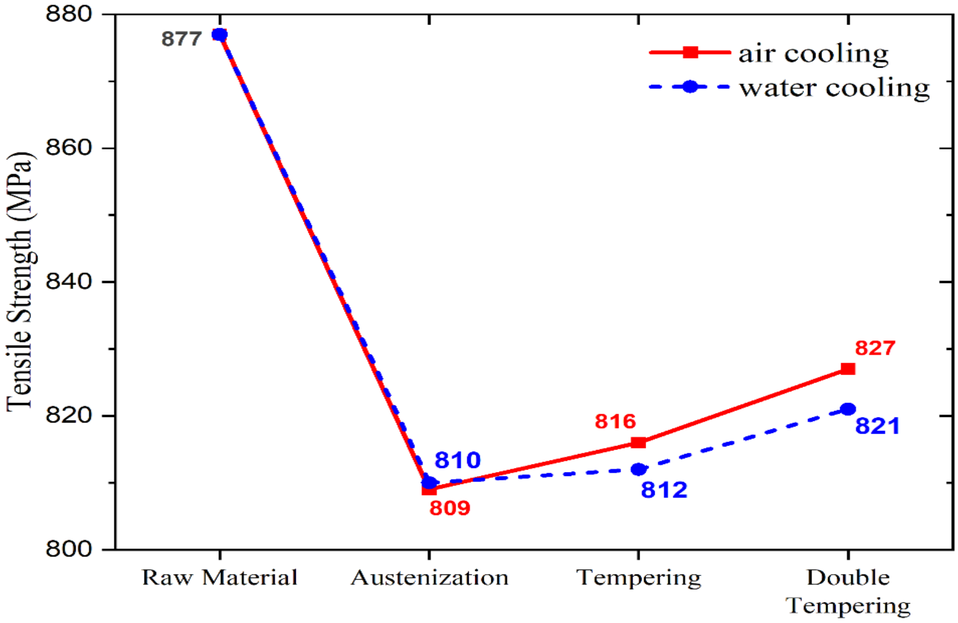

Figure 3 Results of tensile testing.

As illustrated in Figure 3, the double tempering process, when combined with hot rolling, decreases the tensile strength of medium manganese steel from an initial 877 MPa to 827 MPa for air cooling and 821 MPa for water cooling. This phenomenon is attributed to the double tempering process facilitating a more uniform distribution of carbon, thereby increasing the hardness of the material (Bandanadjaja & Idamayanti, 2020). Consequently, as the material hardens, its tensile strength diminishes (Pranata et al., 2020). However, it is noteworthy that the austenization, tempering, and double tempering processes enhance the toughness of medium manganese steel. The toughness value escalates from an initial 809 MPa to 827 MPa with air cooling and from 810 MPa to 821 MPa with water cooling. This increase in tensile strength is induced by deformation, which results in grain density and strain hardening due to compression during the hot rolling process (Rosa & Suhdi, 2016). The tensile test results further reveal that air cooling yields superior toughness compared to water cooling, suggesting that the air cooling process or normalizing can restore the ductility of steel, as evidenced by the increased tensile test results (Sardi et al., 2018).

3.3 Metallographic Observations

Observations of metallography were conducted utilizing an Olympus U-MSSP4 microscope, employing a magnification factor of 20 times. The primary objective of these metallographic examinations is to identify the various phases that have formed within the specimen.

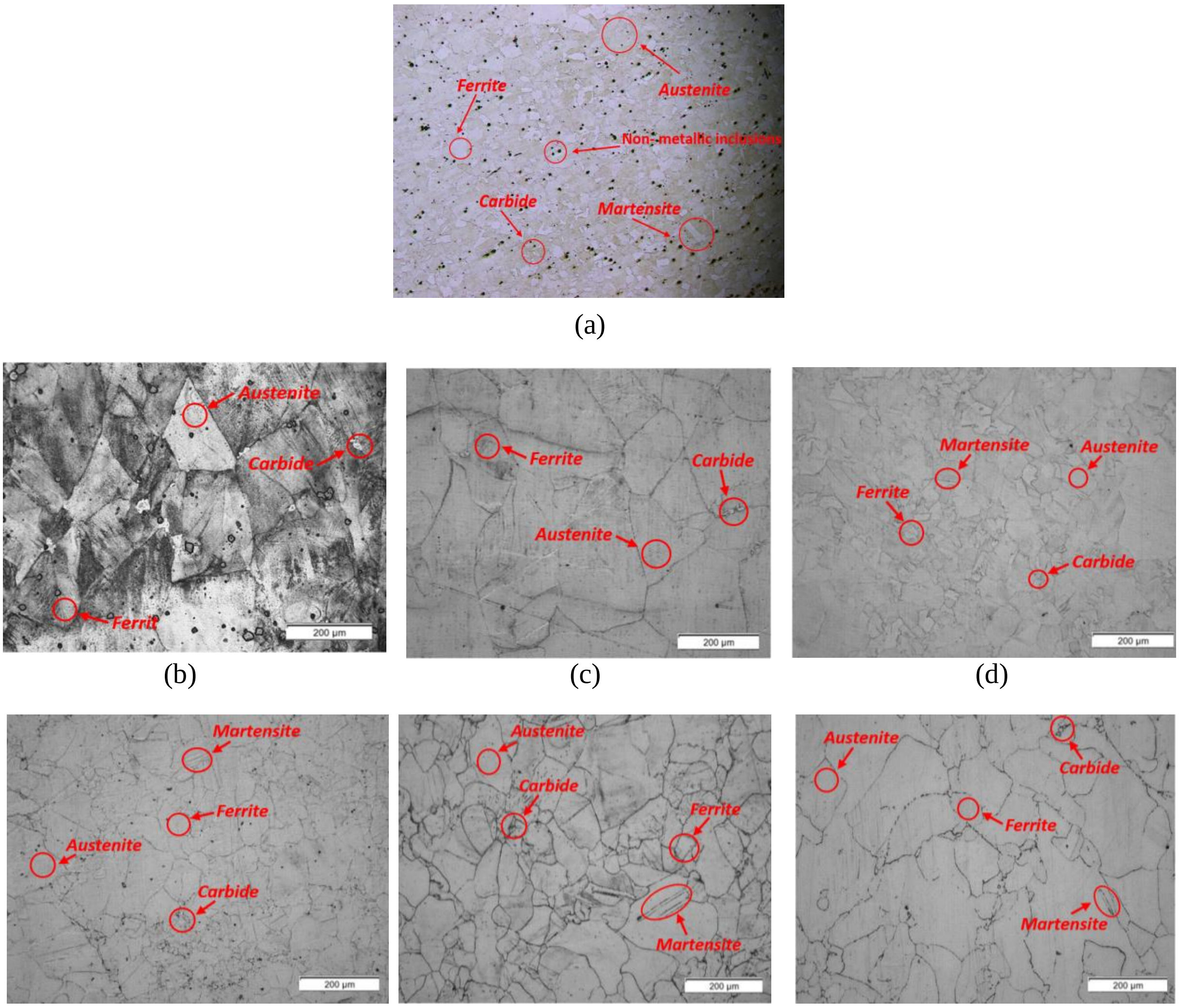

Figure 4 Metallography of (a) Raw Material, (b) Austenization 900°C Air Cooling, (c) Austenization 900°C Water Cooling, (d) Tempering 650°C Air Cooling, (e) Tempering 650°C Water Cooling, (f) Double Tempering 600°C Air Cooling, and (g) Double Tempering 600°C Water Cooling.

Figure 4 shows the raw material consisting of austenite, ferrite, martensite, and carbide phases, with austenite being the predominant phase, consistent with the main structure of medium manganese steel (Azmy et al., 2021). The determination of the formed phases results from observations of the sample's surface that have been etched using an optical microscope. The etching solution used is a 2% initial made by mixing 98% methanol (CH_3OH) and 2% nitric acid (HNO_3) adjusted to the sample composition to enhance the optical visibility of its microstructure. The observations show that each phase has distinctive and different morphologies (Petzow, 1999).

The austenization process at 900°C, followed by air or water cooling, yielded austenite as the dominant phase, along with ferrite and carbide phases, agrees with the Fe-Mn alloy phase diagram, which states that steel with 12% manganese content at temperatures above 650°C has a higher proportion of austenite (γ) than ferrite (α) (Baker & Okamoto, 1992).

For the tempering process at 650°C, followed by air or water cooling, austenite, ferrite, martensite, and carbide phases were observed. The emergence of the martensitic phase contributed to the increased hardness of medium manganese steel. In this process, it was also evident that the morphology of the air-cooled sample exhibited more dispersed and uniform carbides compared to the water-cooled sample, which explains why the hardness value for air cooling was higher than that for water cooling (Paristiawan et al., 2021).

For the double tempering process at 600°C, followed by air or water cooling, austenite, ferrite, martensite, and carbide phases were also detected. It was apparent that after the double tempering process, there was more martensite than during the tempering process. The martensite phase resulted from the delayed transformation of carbon to form the BCT crystal structure. This needle-like phase increased the hardness of the material (Herbirowo & Adjiantoro, 2016). Moreover, the double-tempering process produced more carbides, especially in the air-cooled sample, and some carbides were found in the grains, indicating soluble carbides by a white phase (Ridlo et al., 2020). The carbide found is in the form of a smooth spheroid, which is able to withstand plastic deformation so that the metal will still have quite high strength. Thus, the metal becomes strong and ductile overall (Herbirowo & Adjiantoro, 2016). The metallographic results also show no evidence of carbide accumulation at the grain boundaries. The presence of carbides in the austenite matrix and the absence of carbide accumulation at the grain boundaries can increase the strength of medium manganese steel (Paristiawan et al., 2023).

3.4 Fractographic SEM Testing

Scanning Electron Microscopy (SEM) fractography testing was conducted to provide a detailed examination of the fracture morphology. This analysis was performed using a JEOL JSM 6390A SEM machine with a magnification factor of 500 times. The test results facilitated the identification of various fracture types, including brittle, ductile, and mixed fractures. Brittle fractures, characterized by a flat fracture surface, were indicated by cleavage. In contrast, ductile fractures were identified by the presence of dimples, which are indicative of a fibrous fracture surface. Mixed fractures represent a combination of brittle and ductile fractures (Zuhaimi, 2016).

SEM fractography revealed that most fractures in raw materials and samples austenized at 900°C (with either air or water cooling) were dimpled with minimal cleavage, indicating a predominantly ductile fracture structure. This fracture type suggests that the sample exhibits good plastic deformation, resulting in ductile and tough properties (Faruq et al., 2018). The formation of ductile fractures indicates an increase in the sample's toughness (Yoto & Widiyanti, 2016).

In the tempering process conducted at 600°C, both air and water-cooled samples exhibited a balanced distribution of cleavage and dimple fractures. This balance suggests that the fractures were mixed, encompassing both brittle and ductile fractures (Bahfie et al., 2020). A similar observation was made in the double tempering process, where mixed fractures in cleavage and dimple were evident. However, it is worth noting that the cleavage area was slightly larger than the dimples. Despite this, the sample balanced hardness and toughness (Santosa & Jimi, 2018). Interestingly, even though the double tempering process resulted in a slightly larger cleavage area, this was counterbalanced by a tenacious dimple area. The results of these fracture tests are illustrated in Figure 5.

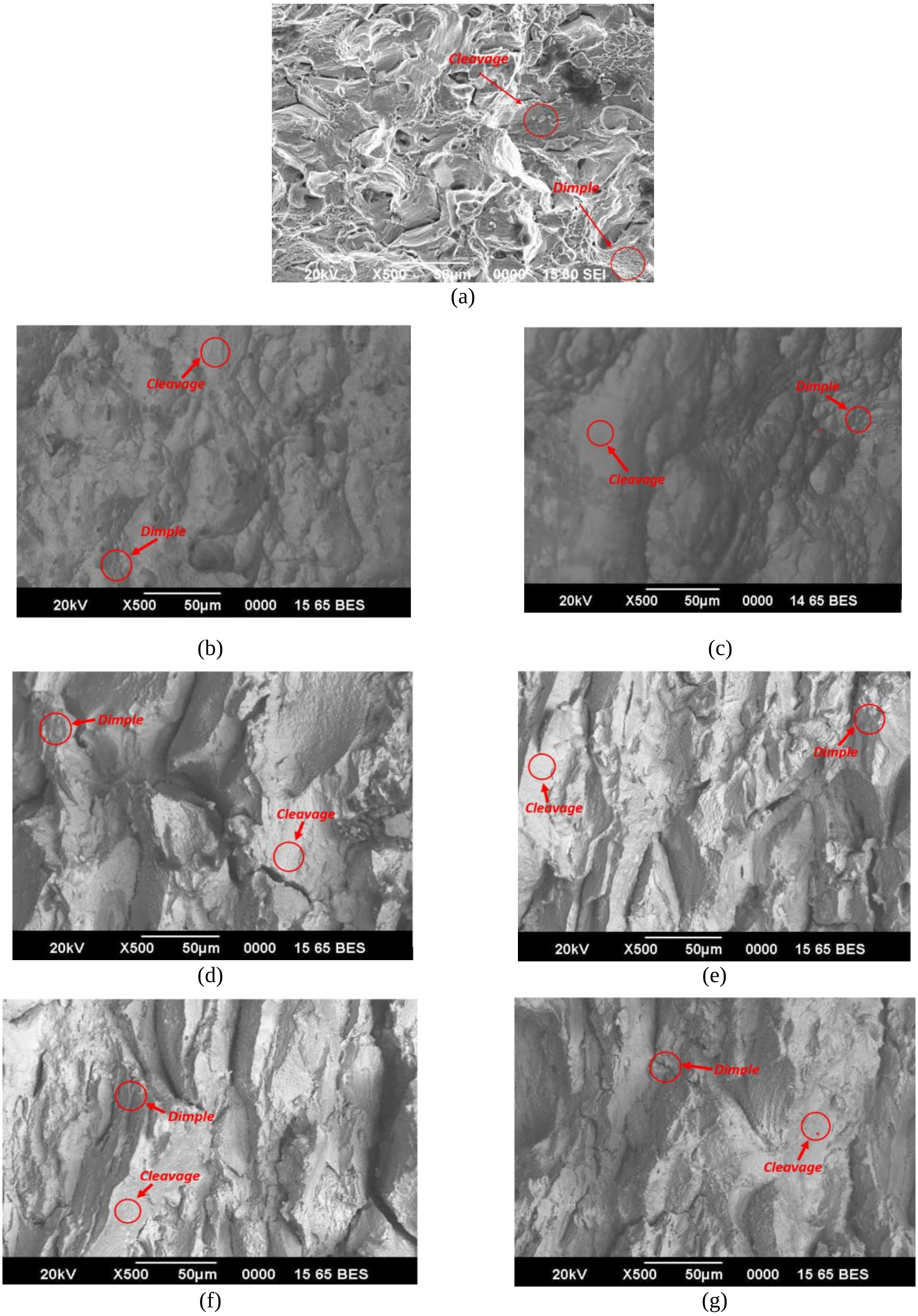

Figure 5 Fractography of (a) Raw Material, (b) Austenization 900°C Air Cooling, (c) Austenization 900°C Water Cooling, (d) Tempering 650°C Air Cooling, (e) Tempering 650°C Water Cooling, (f) Double Tempering 600°C Air Cooling, and (g) Double Tempering 600°C Water Cooling.

4. CONCLUSION

This research has made significant strides in enhancing the hardness of medium manganese steel through a meticulous process of double tempering, hot rolling, and variations in cooling media. The hardness testing results show that air cooling emerged as the most effective medium, yielding the highest hardness value of 389.70 BHN, coupled with a tensile strength of 827 MPa. This notable increase in hardness can be attributed to the emergence of the martensite phase and the presence of substantial amounts of carbide, which were observed to be more evenly distributed following the double-tempering process. In addition to this, a small quantity of carbide was discerned within the austenite matrix, further contributing to the hardness of the material. The SEM fractography testing provided valuable insights into the nature of fractures within the material. The fractures were found to be mixed in nature, characterized by a slightly larger cleavage area than the dimple area. This observation is particularly significant as it suggests that despite the high hardness value, the sample retains commendable toughness.

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