



## Microstructural evolution and mechanical performance of Ni-modified sand-cast excavator bucket teeth

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### Abstract

Excavator bucket teeth require high strength, hardness, and impact toughness to withstand severe service conditions involving abrasion and repeated impact. Achieving this combination of properties in sand-cast low-alloy steels remains challenging. This study investigates the microstructural evolution and mechanical properties of nickel-modified sand-cast bucket teeth subjected to a five-step heat treatment process. The material was produced by sand casting with the addition of 0.6 wt.% Ni, followed by sequential heat treatment consisting of normalizing, pre-tempering, quenching, and double tempering. Microstructural characterization and mechanical testing were conducted to evaluate the effects of the heat-treatment sequence on material performance. The applied heat treatment produced a lath martensite as the dominant microstructure with the presence of retained austenite. After the final tempering stage, the tensile strength reached 1206 MPa, with a hardness of 51 HRC, and an impact toughness of 26.1 J/mm<sup>2</sup>. The improved impact resistance is associated with retained austenite promoted by nickel addition. Fractographic analysis revealed predominantly ductile fracture characterized by dimple formation, followed by crack propagation involving intergranular and secondary cracking features. These results demonstrate that nickel modification combined with heat treatment effectively improves the mechanical performance of sand-cast bucket teeth.

### Keywords:

Bucket teeth, nickel addition, low-alloy steel, heat treatment, excavator.

### 1 Introduction

The demand for heavy equipment in the construction and mining sectors has risen markedly in recent years. Among various types of machinery, excavators play a critical role and are widely utilized for operations such as digging, cleaning, and mining activities [1, 2]. Bucket teeth are among the most essential components of excavators, as they are directly exposed to severe service conditions [3]. Positioned at the front of the excavator, bucket teeth come into direct contact with rocks and mineral materials during operation. Under such demanding conditions, bucket teeth are prone to wear, plastic deformation, and fracture. These failure mechanisms result in frequent replacements and consequently lead to a relatively short service life of the

components [4, 5]. Therefore, the development of materials exhibiting a balanced combination of high strength, high toughness, and excellent wear resistance is critically required for bucket teeth applications [5].

One of the key challenges in materials science is achieving an optimal balance among strength, toughness, and wear resistance [6]. Enhancing wear resistance is commonly associated with the use of materials possessing high hardness [7]. Nevertheless, increasing hardness often leads to a reduction in toughness, which is detrimental to the performance of bucket teeth. Although this trade-off can be mitigated through the addition of specific alloying elements, such an approach inevitably increases the overall material cost [8, 9]. Consequently, the development of materials that combine adequate toughness with reduced cost remains a primary focus of ongoing research efforts [10, 11].

Medium carbon steel is widely recommended for bucket teeth applications due to its balanced mechanical properties. However, its performance can be further enhanced by adding alloying elements to improve both mechanical and physical characteristics. In an effort to enhance the properties of medium-carbon steel, Keles et al. [12] introduced titanium (Ti) additions of 0.15 and 0.20 wt.% via the sand-casting process. The incorporation of Ti promoted the formation of carbide particles and titanium nitride (TiN), which exhibit high hardness but are inherently brittle.

Alternative alloying strategies have also been reported. Jiang et al. [11] successfully added niobium (Nb) to maraging steel, achieving a tensile strength of 2 GPa and an elongation of 8.0%. Similarly, He et al. [10] demonstrated that vanadium (V) addition could yield a tensile strength of 2.2 GPa with an elongation of 15%. The use of carbide-stabilizing elements such as Nb, Ti, and V has therefore been recognized as an effective approach to enhancing the mechanical properties of steel [13-16]. Nevertheless, the high cost of these alloying elements remains a significant limitation. Nickel (Ni) has emerged as a promising alternative alloying element due to its relatively lower cost and its ability to dissolve in the ferritic matrix, thereby enhancing the mechanical properties of medium-carbon steel through solid-solution strengthening [17-20]. In addition, Ni acts as a strong austenite stabilizer, and contributes to improved corrosion resistance in medium-carbon steel. Previous studies have reported that moderate additions of Ni can improve the mechanical performance of steels; however, excessive Ni content may lead to undesirable microstructural effects. For example, Park et al. [20] reported that increasing Ni content in medium-carbon ultra-strong steels resulted in a higher fraction of undissolved cementite (Fe<sub>3</sub>C) in the martensitic matrix, which negatively affected tensile strength. Their study suggested that the optimal Ni content lies within a moderate range of approximately 0.3-1.2 wt.%. Based on these considerations, a Ni content of 0.6 wt.% was selected in the present study as a moderate alloying level expected to enhance mechanical properties while avoiding the adverse microstructural effects associated with higher Ni concentrations.

In addition to alloying strategies, modifying heat-treatment parameters is an effective approach to enhance the mechanical properties of steel [21]. Elshaer et al. [1] reported that heating steel to 900°C followed by quenching in a salt bath at temperatures of 220 and 270°C resulted in a tensile strength of 1492 MPa, a hardness of 474 HV, and an impact energy of 14 J. Similarly, Suryo et al. [22] investigated the effects of austenitization at temperatures of 850, 875, and 900°C with varying holding times, followed by quenching and subsequent tempering at 250, 450, and 650°C. Their results indicated that the optimum hardness was achieved at an austenitization temperature of 875°C with water as the quenching medium, combined with a tempering temperature of 250°C.

This study focuses on the development of a low-cost, low-alloy steel with a favorable balance of mechanical strength for bucket teeth applications. The effects of Ni addition and heat treatment modification on the microstructure, mechanical properties, and fracture behavior of the low-alloy steel were systematically

investigated. Although previous studies have investigated alloying strategies and heat-treatment optimization in steels, the combined effects of nickel modification and multi-stage heat treatment on sand-cast bucket teeth materials remain insufficiently explored. In addition, the bucket teeth components were fabricated by the sand casting method to reflect practical manufacturing conditions.

## 2 Research methodology

### 2.1 Preparation

This study employed low-alloy steel with a chemical composition conforming to the GS30Mn5 standard. The raw materials consisted of steel scrap, chromium steel, nickel sheets, ferromolybdenum, ferromanganese, and ferrosilicon. The casting process was conducted in an Inductotherm medium-frequency open-atmosphere induction furnace with a capacity of 250 kg, and aluminum (Al) was used as a deoxidizing agent during melting. Ni sheets were added to the furnace during the melting stage to achieve a target nickel content of 0.6 wt.%. The entire melting process was completed within approximately 2.5-3 hours. Chemical composition analysis was performed in situ during melting using Optical Emission Spectrometry (OES; ARL 3460, Switzerland). The resulting chemical composition of the low-alloy steel is summarized in Table 1.

Table 1. Chemical composition of the low-alloy steel with Ni addition used in the present study

Steel	C	Si	Mn	Ni	Cr	Mo	V	Cu	Fe
wt.%	0.31	1.25	1.31	0.61	1.89	0.04	0.01	0.03	Bal.

### 2.2 Heat treatment

After completion of the bucket teeth casting process, the specimens were subjected to a five-step heat treatment sequence, as illustrated in Fig. 1. In the first step, the bucket teeth were heated to 970°C for 3 hours, followed by air cooling. The second step involved tempering at 350°C for 3 hours, followed by water cooling. Subsequently, the bucket teeth were austenitized at 925°C for 1 hour and then quenched in water at room temperature (around 25°C) as the cooling medium. The specimens were immediately transferred from the furnace to the quenching bath to ensure rapid cooling. The final stage consisted of a double-tempering treatment at 200°C for 4 hours, followed by water cooling to room temperature. The initial normalizing and pre-tempering steps were intended to refine the grain size and promote a more homogeneous microstructure, whereas the quenching and double-tempering treatments were applied to enhance the hardness, strength, and toughness of the bucket teeth.

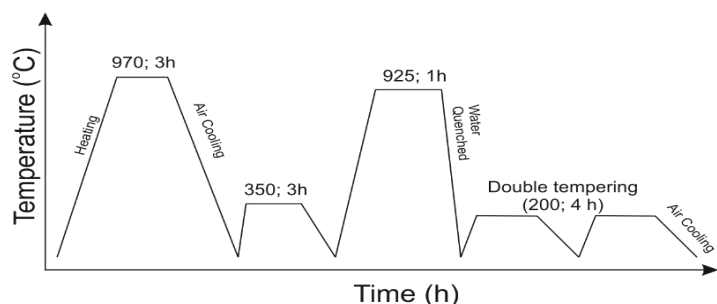


Fig. 1. Heat treatment cycles of the bucket teeth excavator.

### 2.3 Characterizations

Microstructural observations were performed on samples that were sectioned and mechanically ground using SiC papers with grit sizes ranging from 120 to 2000. The samples were subsequently polished using an Al<sub>2</sub>O<sub>3</sub> suspension to obtain a smooth surface. After polishing, the specimens were etched with a 3% Nital solution to reveal the microstructural features. The microstructures were examined using a Scanning Electron Microscope (SEM; Rigaku SU 3500, Japan) operated in Secondary Electron Imaging (SEI) mode.

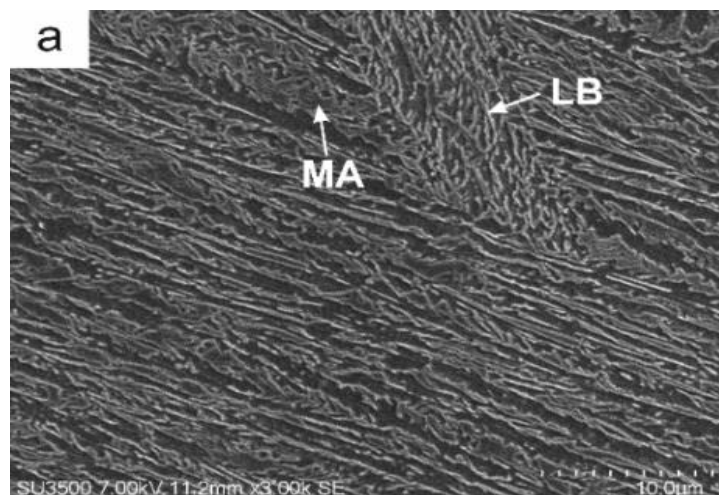
Tensile, hardness, and impact tests were conducted to evaluate the mechanical properties of the bucket teeth. Tensile testing was performed in accordance with the ASTM E8 standard using a Universal Testing Machine (UTM; ZwickRoell, Germany) with a maximum capacity of 20 tons [23]. Hardness measurements were performed using the Rockwell C method with an applied load of 1470 N and a dwell time of 10 s, employing a universal hardness tester (Z25N; ZwickRoell, Germany). The hardness test followed the ASTM E18 standard [24]. Impact testing was conducted using the Charpy impact method in accordance with ASTM E23 [25].

## 3 Results and discussion

### 3.1 Microstructural analysis

Fig. 2 illustrates the microstructures of the bucket teeth material containing 0.6 wt.% Ni subjected to different heat treatment conditions. The sample normalized at 970°C for 3 hours exhibited a microstructure predominantly composed of Lath Bainite (LB), with a small fraction of Martensite/Austenite (M/A) islands, as shown in Fig. 2(a). Following the pre-tempering treatment at 350°C for 3 hours, portions of the bainitic microstructure underwent recovery processes involving carbon diffusion and redistribution from supersaturated bainitic ferrite. These processes reduced the sharp lath morphology and promoted the development of a more equiaxed bainitic ferrite structure accompanied by dispersed M/A constituents, resulting in a granular bainite-like morphology, as shown in Fig. 2(b). The morphology of bainite is strongly influenced by transformation temperature and cooling conditions, where granular bainite generally forms at relatively higher transformation temperatures or lower cooling rates. In contrast, lath-like bainite tends to develop at lower temperatures or higher cooling rates due to differences in bainitic ferrite growth kinetics and carbon partitioning during transformation, as reported in previous studies [26].

After the bucket teeth material was hardened by austenitizing at 925°C for 1 hour, followed by water quenching, a large fraction of martensite formed within the microstructure, as shown in Fig. 2(c). Fig. 2(d) and Fig. 2(e) present the microstructural morphology of the bucket teeth after the double tempering treatment at 200°C. During tempering, the initially thin martensitic laths coarsened and became less oriented, resulting in a microstructure predominantly composed of wider lath martensite accompanied by thin films of Retained Austenite (RA). Martensite can exhibit various morphologies, including butterfly, lenticular, thin-plate, and lath structures [27]. The prevalence of lath martensite at the final stage of heat treatment plays a critical role in determining the mechanical performance of bucket teeth, as both strength and toughness are strongly influenced by the packet and block sizes as well as the morphology of lath martensite [28]. Furthermore, microstructural observations indicate that the addition of nickel to the low-alloy steel does not lead to the formation of secondary phases in the bucket teeth material.



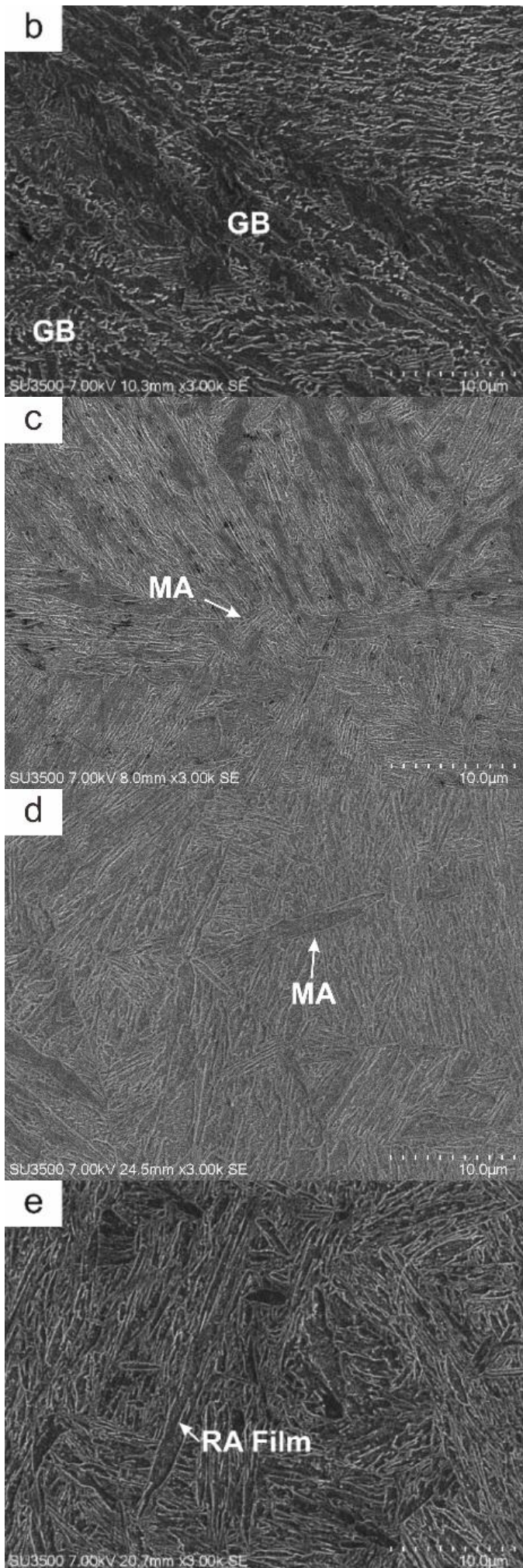


Fig. 2. Microstructure of bucket teeth material with different heat treatment processes (a) normalizing, (b) pre-tempering, (c) quenching, (d) tempering 1, and (e) tempering.

### 3.2 Mechanical properties

Fig. 3 presents the tensile strength values of the bucket-teeth material subjected to different heat-treatment conditions. The results indicate that the normalized and pre-tempered low-alloy steel exhibited lower tensile strength than the other conditions, with values of 976 and 936 MPa, respectively. Following the quenching treatment, the tensile strength increased markedly to 1470 MPa, attributed to the formation of a predominantly martensitic microstructure. Subsequent double tempering led to a slight reduction in tensile strength, yielding 1465 MPa and 1206 MPa for the first and second tempering stages, respectively. This reduction in tensile strength is consistent with the microstructural evolution observed after tempering, in which martensitic laths become wider and less oriented and thin films of retained austenite are stabilized, leading to reduced lattice distortion and dislocation density. The complete tensile test results for all heat-treatment conditions are summarized in Table 2.

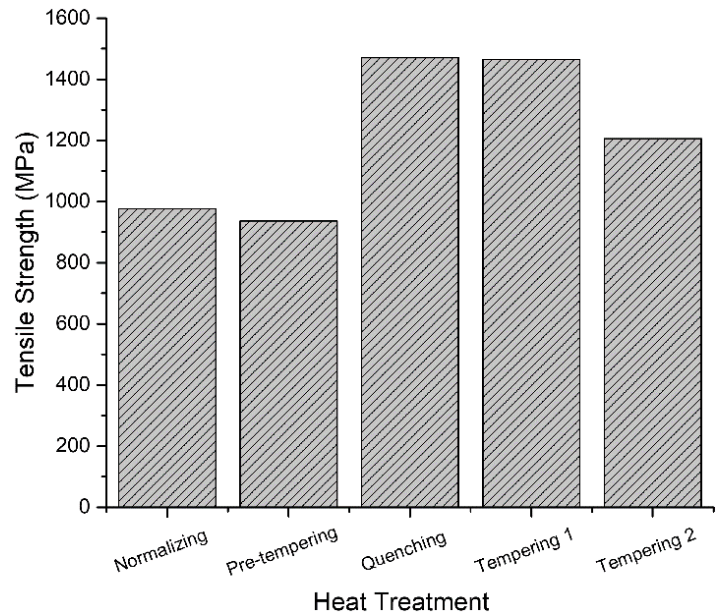


Fig. 3. Tensile strength of bucket teeth material at different heat treatment processes.

Fig. 4 presents the hardness results obtained using the Rockwell C method. The results indicate that the pre-tempering treatment leads to a reduction in the hardness of the bucket teeth material. This reduction is associated with the microstructural evolution of lath bainite containing M/A islands formed during the normalizing process, during which partial decomposition and transformation into granular bainite occur, resulting in lower hardness. During the pre-tempering treatment, recovery processes involving carbon diffusion and redistribution reduce the dislocation density in the bainitic ferrite and promote the formation of a more equiaxed granular bainite-like morphology. Since bainitic structures generally have a lower dislocation density than martensite, the hardness decreases after the pre-tempering treatment. Reheating the material to 925°C and then quenching in water, the austenite rapidly transforms into martensite, which significantly increases the hardness of the material. In contrast, the double tempering treatment conducted at relatively low temperatures does not produce a pronounced change in hardness. The hardness values for each heat treatment condition are summarized in Table 2.

Table 2. Mechanical properties of bucket teeth material under different heat treatment processes

Heat treatment	Tensile strength (MPa)	Hardness (HRC)	Impact strength (J/mm <sup>2</sup> )
Normalizing	976	42	12.30
Pre-tempering	936	38	12.67
Quenching	1470	53	12.04
Tempering 1	1465	52	13.50
Tempering 2	1206	51	26.10

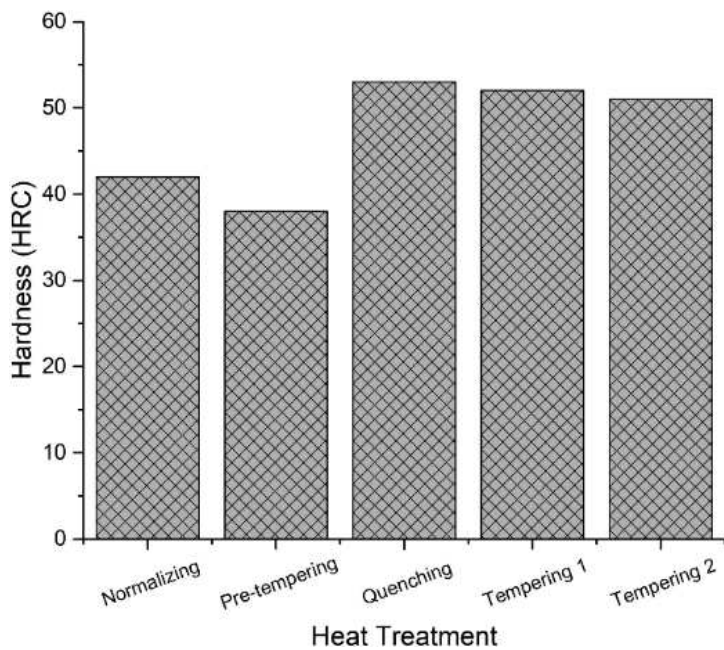


Fig. 4. Hardness value of bucket teeth material at different heat treatment processes.

Fig. 5 presents the results of the Charpy impact tests for the bucket teeth material subjected to various heat treatment conditions. The quenched condition shows relatively low impact energy despite its high tensile strength. This behavior is associated with the formation of untempered martensite after water quenching. Untempered martensite contains high internal stresses and a high density of dislocations due to supersaturated carbon in the martensitic lattice. These characteristics increase brittleness during impact loading, resulting in lower impact energy. As shown in Fig. 5, the highest impact energy was obtained for the bucket teeth material that underwent double tempering. This increase in impact toughness is attributed to the addition of nickel, which promotes the stabilization of retained austenite in the final microstructure. The presence of retained austenite at low temperatures facilitates greater energy absorption during Charpy impact testing, thereby improving the impact resistance of the bucket teeth material [29, 30]. The detailed impact energy values for each heat-treatment condition are summarized in Table 2.

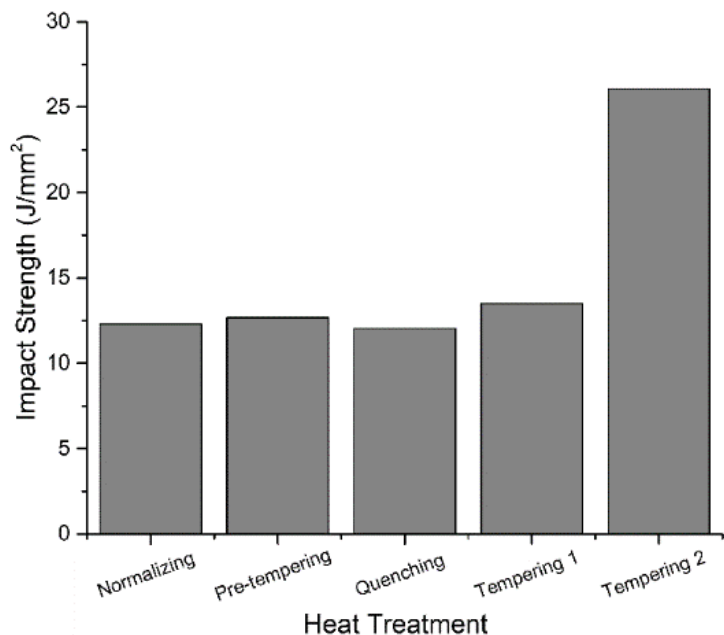


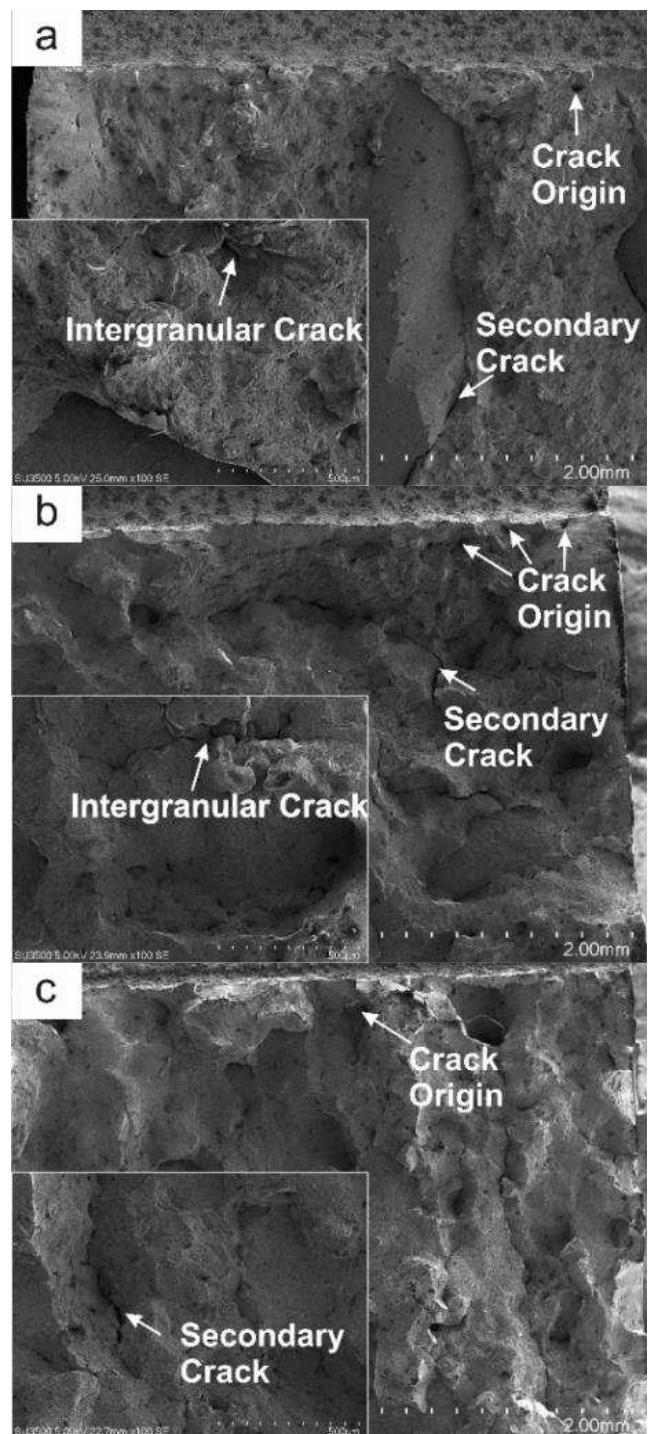
Fig. 5. Impact strength of bucket teeth material at different heat treatment processes.

### 3.3 Fractography of the impact samples

Fig. 6 presents the fractographic analysis of Charpy impact specimens from bucket teeth subjected to different heat treatment

conditions. Distinct features associated with crack initiation and crack propagation regions can be clearly observed on the fracture surfaces. For the normalized and pre-tempered specimens, the crack initiation sites are indicated by white arrows in Fig. 6(a) and Fig. 6(b). Additional crack initiation is evidenced by the presence of large flat regions on the fracture surfaces. These microfracture characteristics include extensive flat areas, intergranular cracking, and secondary cracks.

In the quenched specimen, the number of crack initiation sites (dimples) is reduced, while secondary cracks and large flat cleavage regions become more pronounced. As shown in Fig. 6(c), the fracture surface exhibits a predominantly cleavage fracture mode, which is attributed to the low fraction of retained austenite and the dominance of lath martensite in the microstructure. In contrast, specimens subjected to the double tempering treatment (Fig. 6(d) and Fig. 6(e)) display an increased number of crack initiation sites compared to the quenched condition. This increase in crack-initiation features indicates enhanced energy absorption during fracture, demonstrating that the double-tempering process effectively improves the impact resistance of the bucket-teeth material.



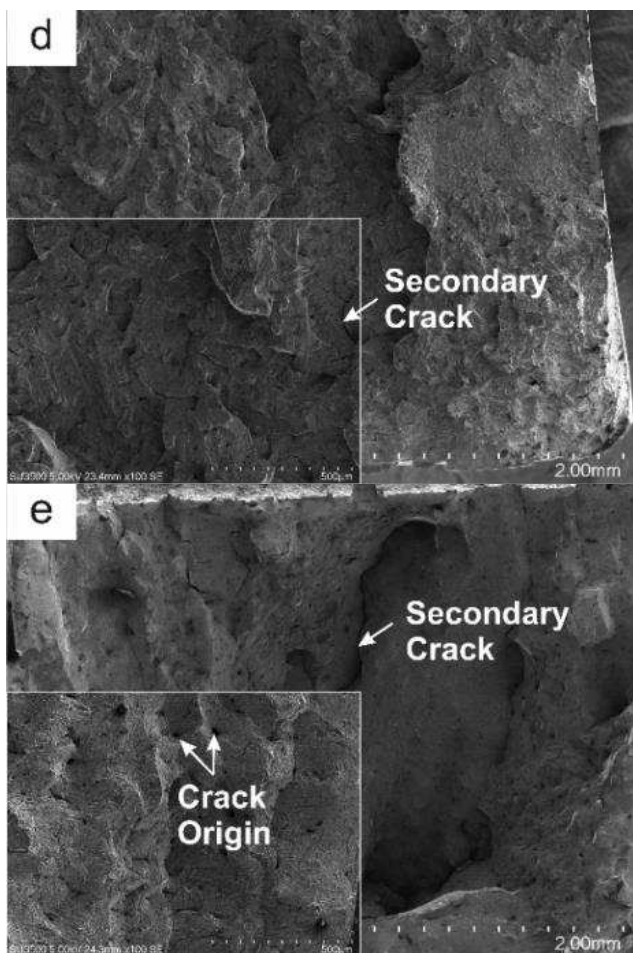


Fig. 6. The fractograph of bucket teeth impact samples after heat treatment process (a) normalizing, (b) pre-tempering, (c) quenching, (d) tempering 1, and (e) tempering 2.

#### 4 Conclusions

A low-cost bucket teeth material containing 0.6 wt.% Ni was fabricated by sand casting method, followed by a five-step heat treatment process. Microstructural characterization (SEM) was conducted using SEI mode, and the mechanical properties, including tensile strength, hardness, and impact strength, were systematically evaluated. The main conclusions of this study are summarized as: (1) the microstructure of the bucket teeth material consisted predominantly of lath bainite and granular bainite after the first two heat treatment stages. In comparison, lath martensite became the dominant phase during the final three heat treatment stages; (2) the tensile strength obtained at the final tempering stage reached 1206 MPa. In addition, the material exhibited high hardness and impact resistance, with values of 51 HRC and 26.10 J/mm<sup>2</sup>, respectively; (3) the improvement in impact strength observed after the double-tempering process is attributed to the formation of retained austenite, which remains stable at low temperatures. The presence of retained austenite plays a key role in enhancing the toughness of the bucket teeth material; (4) Fractographic analysis of the impact-tested samples revealed that fracture initiation occurred at dimple sites, followed by crack propagation characterized by intergranular and secondary cracking mechanisms.

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