LAMPIRAN

Lampiran 1. Tabel Hasil Uji Kekerasan Rockwell

Titik	Spesimen		
	Non Heat Treatment	Normalizing	Annealing
1	77,5 HRC	45 HRC	40,5 HRC
2	76 HRC	46,5 HRC	40 HRC
3	78 HRC	43 HRC	38 HRC
Rata-rata	77,2 HRC	44,8 HRC	39,5 HRC
Deviasi	1,040833	1,755942292	1,322875656

Lampiran 2. Grafik Uji Tarik

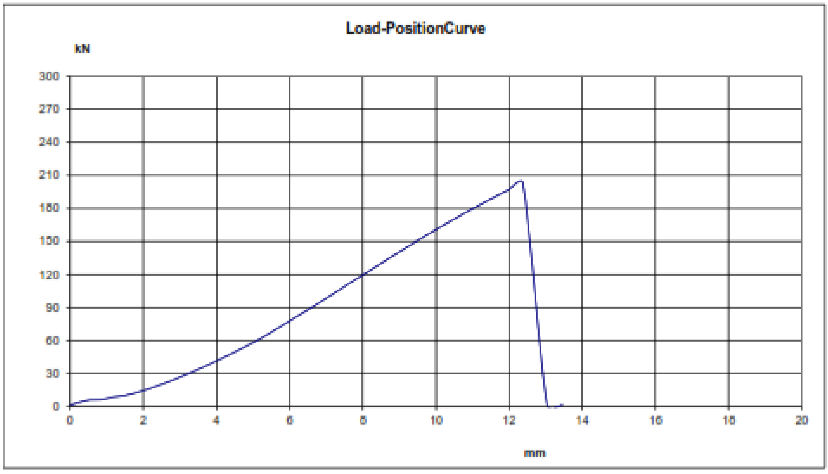
Spesimen Non-*Heat Treatment* 1

Metallic materials-Tensile Testing Report

Standard: BS EN10002-1:2001

	d	du	Lo	Lu	So	Su	ReH	Rm	Fm
	mm	mm	mm	mm	mm^2	mm^2	MPa	MPa	kN
NO.1	16,2		52,2		201,06			1020	205,29

NO.1



Spesimen Non-*Heat Treatment* 2

Metallic materials-Tensile Testing Report

Standard: BS EN10002-1:2001

	d	du	Lo	Lu	So	Su	ReH	Rm	Fm
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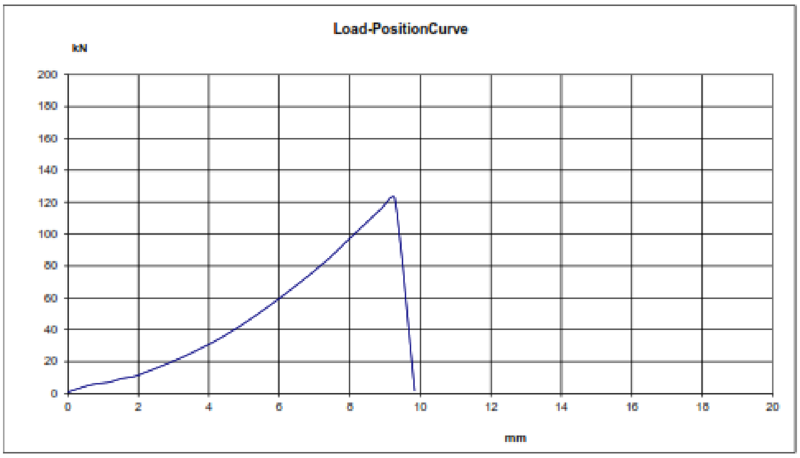
NO.1	16		55		201,06			615	123,16

NO.1



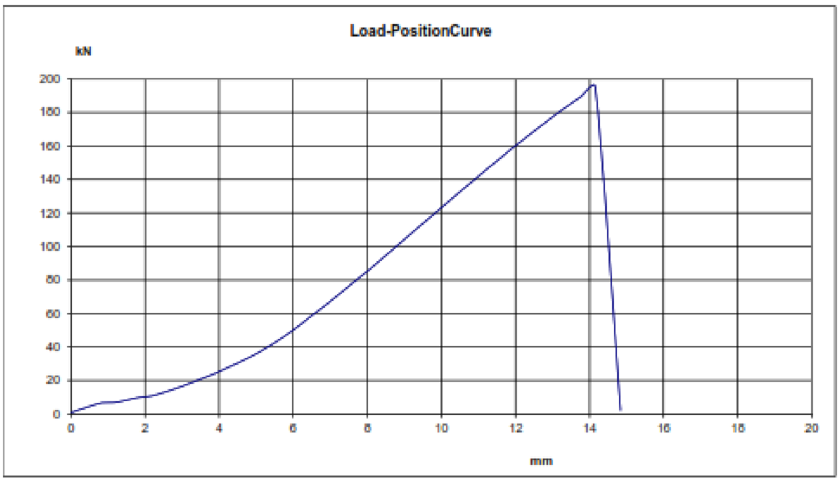
Spesimen Non-*Heat Treatment* 3

Metallic materials-Tensile Testing Report

Standard: BS EN10002-1:2001

	d	du	Lo	Lu	So	Su	ReH	Rm	Fm
	mm	mm	mm	mm	mm^2	mm^2	MPa	MPa	kN
NO.1	16		55		201,06			970	195,15

NO.1



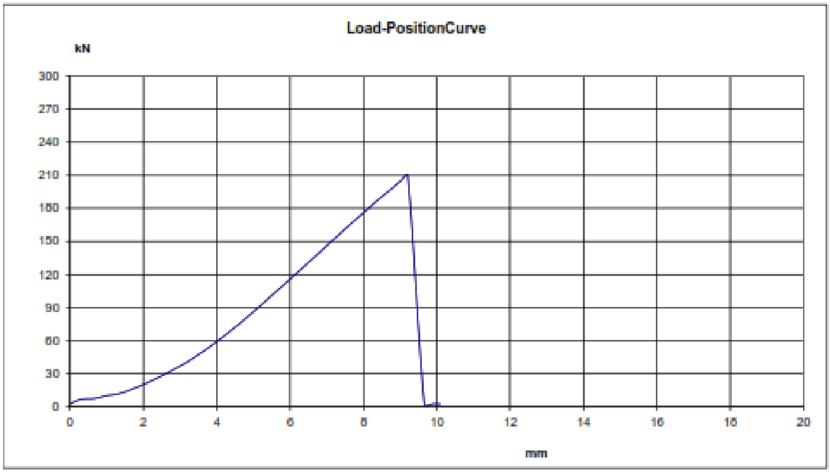
Spesimen *Normalizing* 1

Metallic materials-Tensile Testing Report

Standard: BS EN10002-1:2001

	d	du	Lo	Lu	So	Su	ReH	Rm	Fm
	mm	mm	mm	mm	mm^2	mm^2	MPa	MPa	kN
NO.1	16,2	15,9	50	50	206,12	198,56		1020	210,27

NO.1



Spesimen *Normalizing* 2

Metallic materials-Tensile Testing Report

Standard: BS EN10002-1:2001

	d	du	Lo	Lu	So	Su	ReH	Rm	Fm
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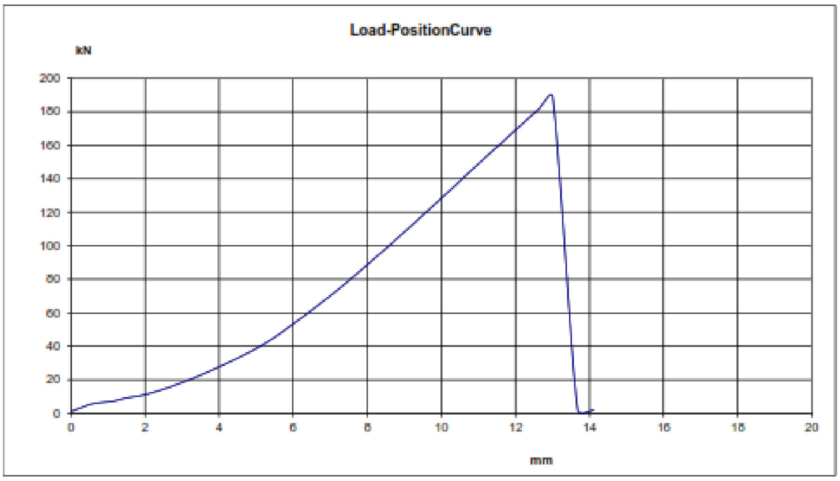
NO.1	16		55		201,06			940	188,87

NO.1



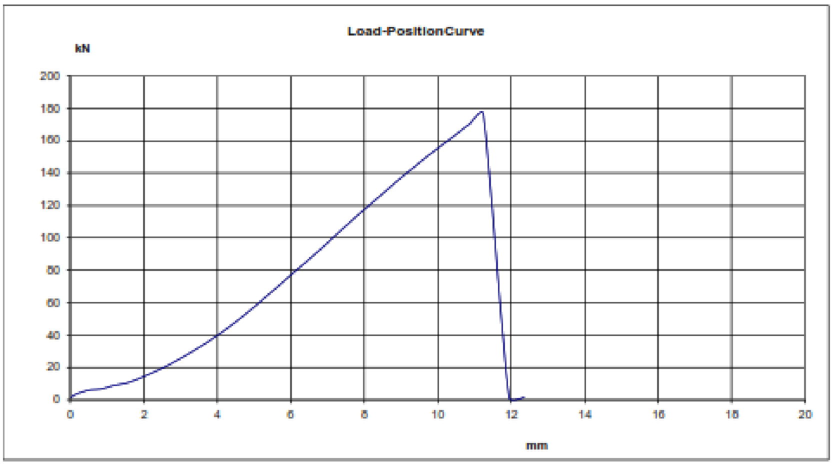
Spesimen *Normalizing* 3

Metallic materials-Tensile Testing Report

Standard: BS EN10002-1:2001

	d	du	Lo	Lu	So	Su	ReH	Rm	Fm
	mm	mm	mm	mm	mm^2	mm^2	MPa	MPa	kN
NO.1	16		53,3		201,06			885	178,19

NO.1



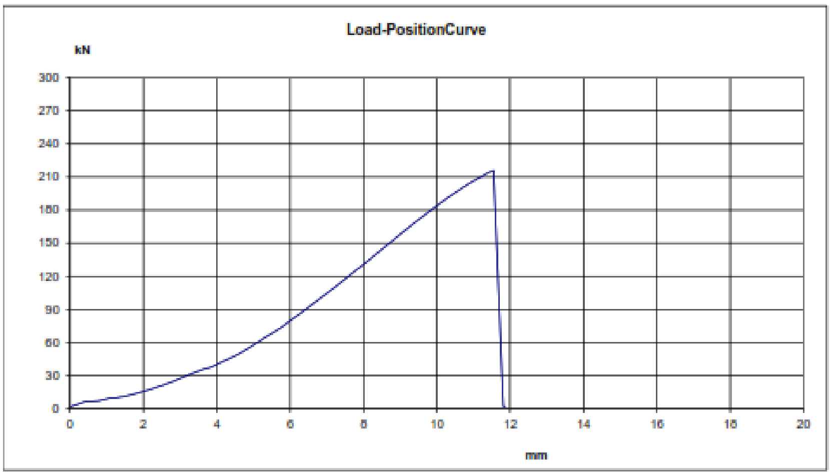
Spesimen *Annealing* 1

Metallic materials-Tensile Testing Report

Standard: BS EN10002-1:2001

	d	du	Lo	Lu	So	Su	ReH	Rm	Fm
	mm	mm	mm	mm	mm^2	mm^2	MPa	MPa	kN
NO.1	16,5	16,2	50	51	213,82	206,12	960	1010	215,81

NO.1



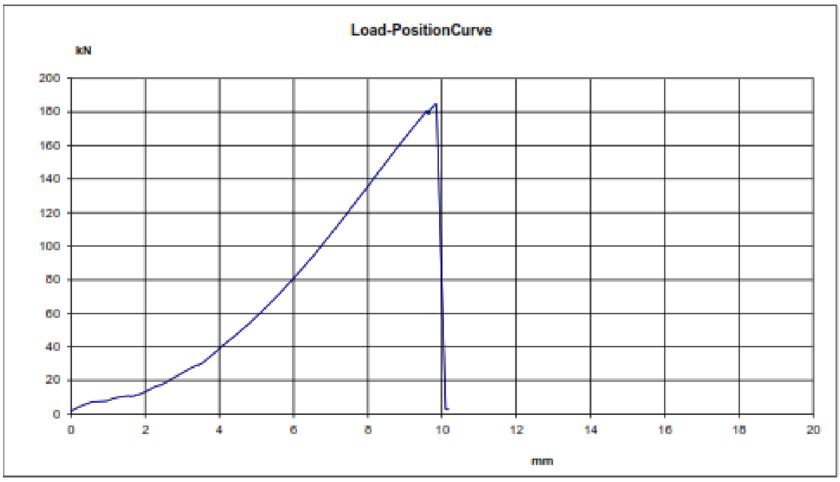
Spesimen *Annealing* 2

Metallic materials-Tensile Testing Report

Standard: BS EN10002-1:2001

	d	du	Lo	Lu	So	Su	ReH	Rm	Fm
	mm	mm	mm	mm	mm^2	mm^2	MPa	MPa	kN
NO.1	16,2	16	50	50,1	206,12	201,06	885	900	185,18

NO.1



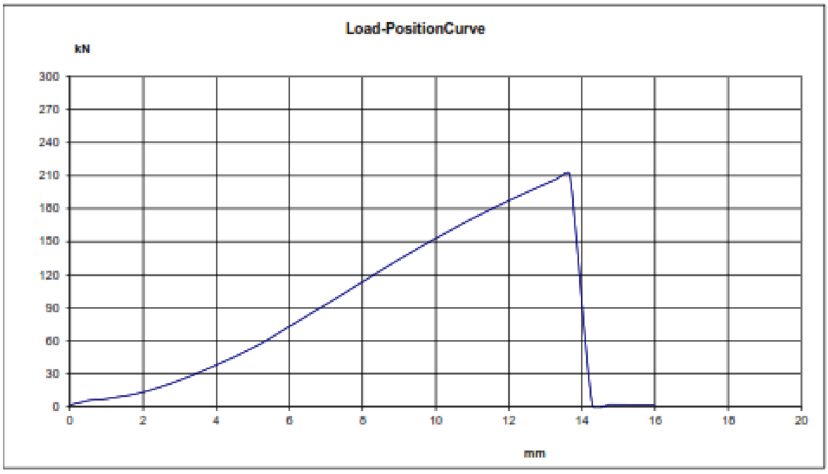
Spesimen *Annealing* 3

Metallic materials-Tensile Testing Report

Standard: BS EN10002-1:2001

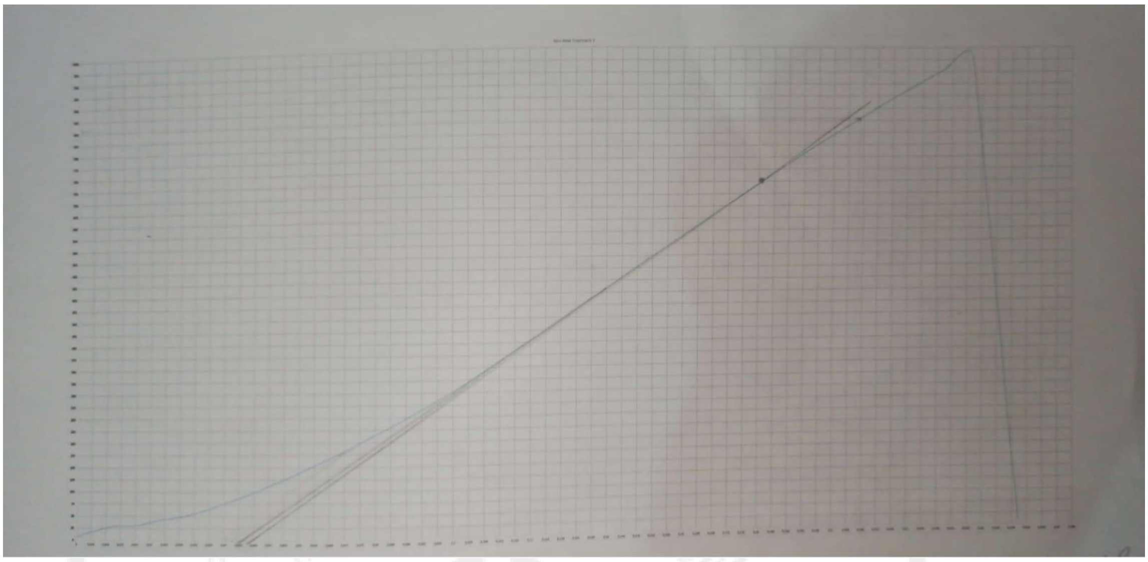
	d	du	Lo	Lu	So	Su	ReH	Rm	Fm
	mm	mm	mm	mm	mm^2	mm^2	MPa	MPa	kN
NO.1	16		55		201,06			1060	213,54

NO.1



Lampiran 3. Perhitungan Modulus Young

Contoh perhitungan modulus young pada spesimen non-*heat treatment* 1 dengan metode offset 0,2%



Diketahui : σ yield = 730 Mpa

ε = 0,18177

Modulus Young

$$E = \frac{\sigma}{\varepsilon}$$

$$E = \frac{730\ MPa}{0{,}18177}$$

$$E = 4016 \text{ MPa} = 4{,}016 \text{ GPa}$$

Lampiran 4. Draft Publikasi

Effect of heat treatment on microstructure and mechanical properties of remelted excavator bucket teeth

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Abstract

This research observes the effect of heat treatment on microstructure, hardness, and tensile strength of remelted low carbon steel from excavator bucket teeth as an effort to reduce bucket teeth waste. Normalizing and annealing heat treatment was done at 900 °C, holding time at 3 hours, and cooled at room temperature and furnace temperature. Result showed decreased of hardness from 77,2 HRC to 44,8 HRC after normalized and 39,5 HRC after annealed due to elimination of brittle microstructure such as martensite. Tensile strength testing showed increased of Ultimate Tensile Strength from 862,7 MPa to 961,3 MPa after normalized and 988,7 MPa after annealed. Increased of elongation from 1,7% to 2,0 % after normalized and 3,3% after annealed, thus showed recovery of ductility.

Keywords: Heat Treatment; Excavator Bucket Teeth; Low Carbon Steel; Remelting; Ni-Cr-Mo

1. Introduction

The increasing human need for energy and minerals is accompanied by the growth in heavy equipment development, one of which is the excavator. Excavators are heavy machinery commonly used in construction or mining to dig and move heavy materials [1]. One of the essential components of an excavator is the bucket teeth, which function to enhance digging power and break hard rock materials during the excavation process [2]. Bucket teeth are required to be made from materials with high hardness, toughness, and wear resistance, such as carbon steel [3]. Bucket teeth undergo periodic replacement when they are damaged due to friction and impacts from hard materials [1]. This regular replacement poses a problem as it results in the accumulation of used bucket teeth waste, necessitating measures to address this waste. Bucket teeth, typically made of carbon steel, can be recycled through the remelting process [3,4].

Carbon steel is one of metals with significant recycling potential, as it has an end-of-life recycling rate (EOL-RR) index of over 50%. The EOL-RR index indicates the percentage of material from waste or discard that can be recycled; the higher the EOL-RR index value, the better the material is for the recycling process [5]. Recycling materials through remelting process has economic benefits as it utilizes used materials while reducing the use of raw materials [6]. However, the remelting process can degrade the mechanical properties of the material in terms of tensile strength and material toughness [7]. However, The mechanical properties of a material can be recovered or enhanced through the alloying process. Alloying is the addition of other materials to the primary material with the aim of improving its mechanical properties. In carbon steel, the addition of alloying elements can enhance hardness, strength, and wear resistance [8]. Casted carbon steel tends to be brittle, thus heat treatment is mandatory to increase its ductility and toughness [9]. Heat treatment is the heating of materials to a specific temperature and then cooling to achieve certain properties [10]. In this study, the heat treatment processes conducted were normalizing and annealing at a holding temperature of 900°C for 3 hours.

Several studies have been conducted to understand the impact of heat treatment on the mechanical properties of cast bucket teeth material. A study by Herbirowo et al. in 2019 showed that the quenching heat treatment process can increase the hardness of cast bucket teeth material [11]. Research by Beny and Dewi in 2017 indicated that tempering and normalizing heat treatments can restore toughness and increase elongation in cast materials [9]. So far, no studies have shown the effects of heat treatment on the mechanical properties of remelted excavator bucket teeth material. This study focuses on the effects of normalizing and annealing heat treatments on the mechanical properties and microstructure of carbon steel material resulting from the remelting of excavator bucket teeth.

2. Experimental

2.1. Material

The material used in this study is a Ni-Cr-Mo alloyed carbon steel remelted from excavator bucket teeth waste, which was then cast using sand casting method with the composition shown in Table 1. The sand casting process was conducted at a pouring temperature of 1500°C.

2.2. Structure

The heat treatment processes conducted were normalizing and annealing with a holding temperature of 900°C and a holding time of 3 hours. The cooling rate varied for each treatment type, where the normalizing specimens were cooled in free air, while the annealing specimens were cooled inside the furnace. The list of specimens is shown in Table 2.

2.3. Microstructural Characterization

Microstructure observation was carried out using a nital etching solution, which consisted of a mixture of 95 ml C2H5OH (ethanol) and 5 ml HNO3 (nitric acid) [12]. Observations were made using a Euromex bScope optical microscope.

2.4. Mechanical Testing

The specimen tests conducted consisted of Rockwell hardness test and tensile strength tes. The Rockwell hardness test was performed with C indenter and a major load of 150 Kgf, in accordance with standard E18-16. The tensile test was carried out using a Universal Testing Machine following the ASTM E8/E8M standard, and the tensile test specimen image can be seen in Fig. 1.

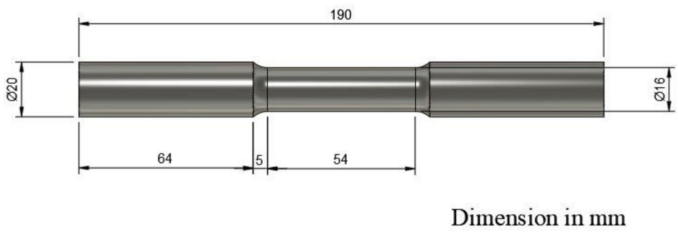

Fig. 1 Tensile Test Speciment

Table 1. Material Composition

Element	Remelted Bucket Teeth (%)
Fe	91.54
C	0.237
Si	0.228
Mn	1.12
Cr	2.50
Mo	0.743
Ni	2.56
Al	0.692
Cu	0.756
Ti	0.903

3. Result

3.1. Microstructure Observation

The microstructure analysis (Figs. 2) of the three specimens indicated a transformation from hard and brittle structures to softer and more ductile ones after undergoing the heat treatment processes of normalizing and annealing.

3.2. Mechanical Properties

The result of hardness and tensile strength test of the Non-heat treated, Normalized, and Annealed specimen are given in Table 3.

3.3. Fracture Morphology

The fracture morphology on tensile test specimen after testing shows an intergranular fracture (Figs. 3) with cleavage fracture (Figs. 4) that occurs in the fracture zone.

Table 2. Result Mechanical Testing

Specimens	Hardness (HRC)	Ultimate Tensile Strength (Mpa)	Yield Strength (MPa)	Elongation (%)	Young's Modulus (GPa)
Non-Heat Treated Specimen	77.2	862.7	690.3	1.7	3.7
Normalized Specimen	44.8	961.3	568.3	2.0	4.2
Annealed Specimen	39.5	988.7	546.7	3.3	3.8

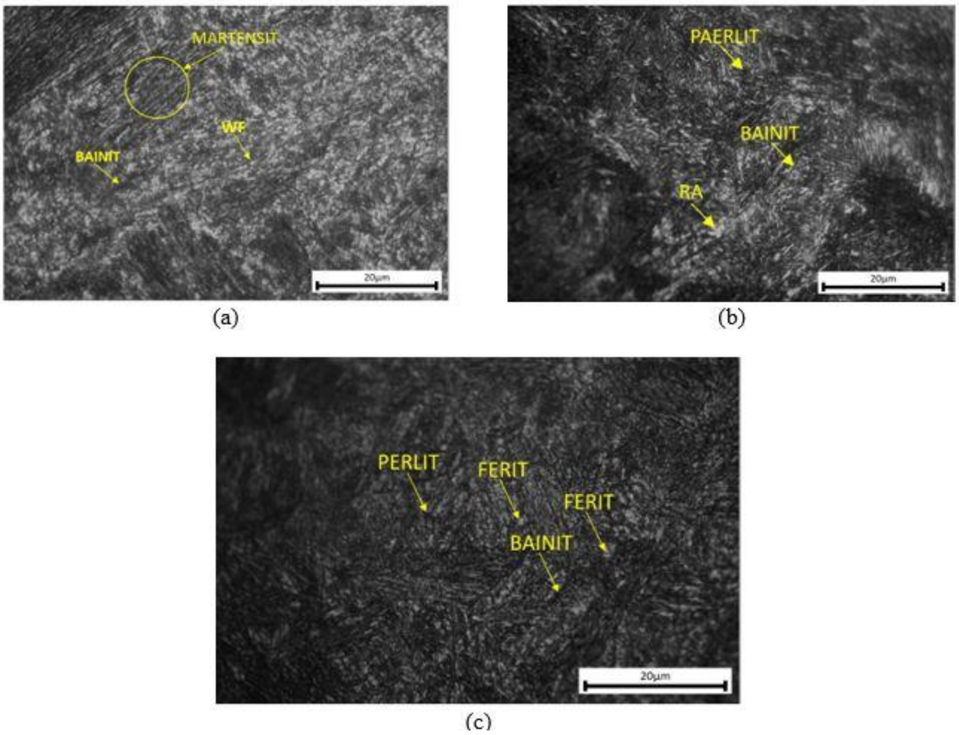

Fig. 2. (a) Non-Heat Treated Specimen; (b) Normalized Specimen; (c) Annealed Specimen Microstructures.

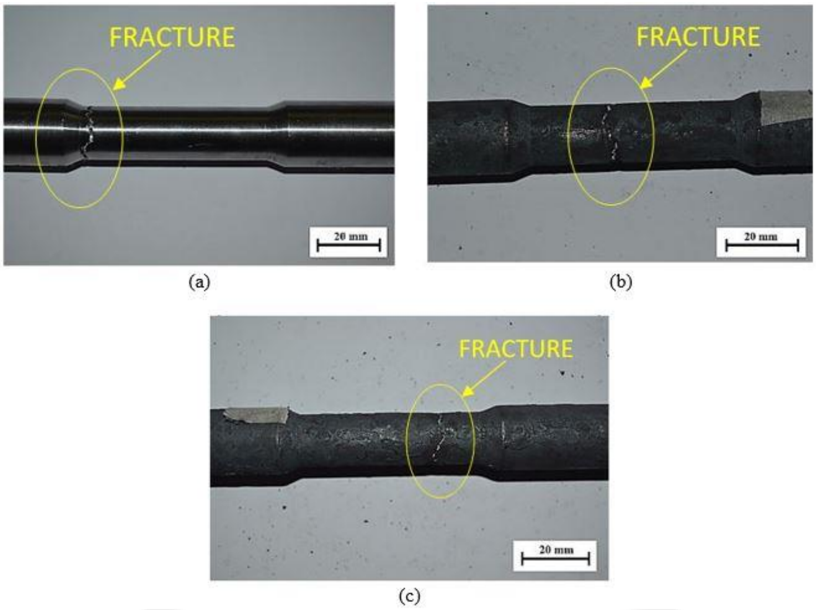

Fig. 3. (a) Non-Heat Treated Specimen; (b) Normalized Specimen; (c) Annealed Specimen Fracture Morphology.

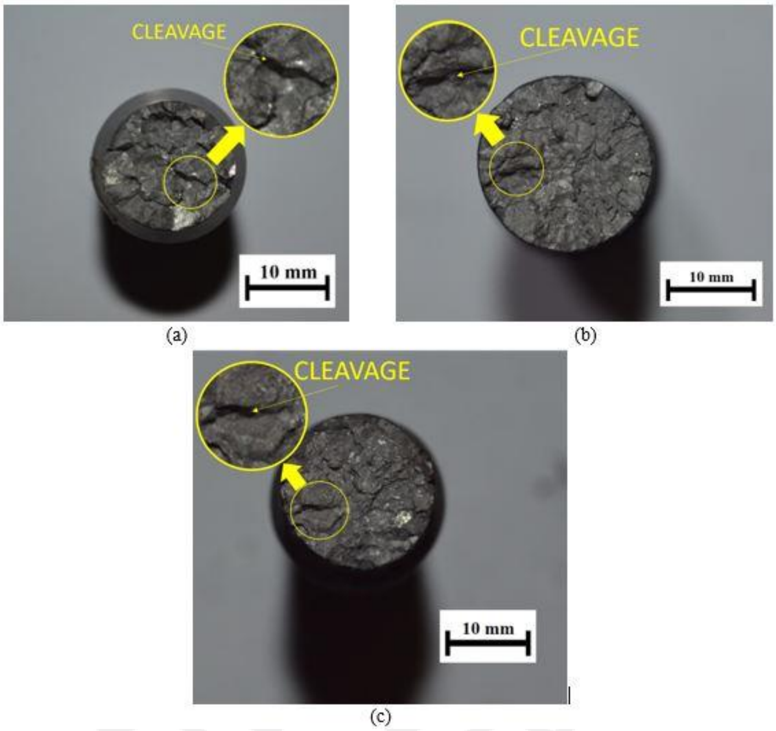

Fig. 4. (a) Non-Heat Treated Specimen; (b) Normalized Specimen; (c) Annealed Specimen Fracture Phenomenon at fracture zone.

4. Discussion

The hardness value of the specimens decreases as heat treatment is applied. The highest hardness value is found in the non-heat-treated specimen with an average value of 77.2 HRC, while the specimen with the lowest hardness is found in the annealing specimen with an average value of 39.5 HRC. The high hardness in the non-heat treated specimen is attributed to the presence of martensite and widmanstatten ferrite structures, which are hard and brittle [13]. The decline in hardness in the normalized specimen occurs due to the disappearance of the widmanstatten ferrite structure and the transformation of the martensite structure to bainite as a result of the heat treatment process, with holding in the austenite zone and cooling at a relatively low rate. The hardness value in the normalized specimen remains relatively high due to the presence of retained austenite and bainite structures in its microstructure. The annealed specimen has the lowest hardness value because its microstructure is dominated by the ferrite and pearlite phases due to the slow cooling rate. The ferrite phase has the lowest hardness compared to other microstructures. In this case, the pearlite structure has a higher ferrite percentage compared to cementite due to the material's low carbon content [14].

The presence of a martensitic structure in the non-heat-treated specimen, as seen in Figs. 2, which is brittle in nature, results in a relatively low ultimate tensile strength and elongation, but it has a higher yield strength compared to the specimens that underwent heat treatment. The dominance of the martensite structure and the internal stress from the casting process lead to a relatively high yield strength in the non-heat treated specimen [15]. Meanwhile, the normalized specimen experienced an increase in UTS and elongation due to the transformation of the martensite structure to bainite from the heat treatment process with a low cooling rate [16]. In the annealed specimen, there is the highest increase in UTS and elongation, attributed to its microstructure being dominated by the soft ferrite and pearlite phases. Unlike the normalized specimen, the annealing specimen doesn't contain retained austenite. This is because, during the heat treatment process with very slow cooling, the austenite can fully transform. In certain concentrations, the presence of retained austenite in materials can lead to a decrease in material strength [10].

The highest Young's modulus is found in the normalizing specimen, with an average value of 4.2 GPa. The lowest Young's modulus is in the non-heat-treated specimen with an average value of 3.7 GPa. The increase in Young's modulus in the normalizing specimen is attributed to the grain refinement process due to heat treatment. Additionally, the presence of bainite and pearlite, which are brittle in nature and present in high percentages, also influences the increase in Young's modulus [10]. Conversely, the annealing specimen, dominated by the softer ferrite phase, results in a relatively lower Young's modulus.

As seen in Figs. 3 the fracture form of the specimen after undergoing tensile strength testing. The jagged fracture shape indicates the occurrence of an intergranular fracture. Intergranular fracture is a type of break that occurs at the grain boundaries, so the resulting fracture is not straight but follows the shape of the grain boundaries [17]. The fact that the fracture cross-section did not experience necking before the fracture occurred suggests that the fracture is of a brittle nature [18]. The cleavage fracture pattern (Figs. 4) in the fracture zone indicates a brittle fracture mechanism.

5. Conclusion

From the results and discussion, the following conclusions can be drawn:

1. The heat treatment process can eliminate brittle microstructures and phases, such as martensite, and transform them into softer and more ductile microstructures, like ferrite. This transformation is attributed to the holding time and cooling rate during the heat treatment process.
2. The normalizing and annealing heat treatments can reduce the material's hardness value and enhance the maximum tensile strength and elongation values of the material derived from the remelting of excavator bucket teeth, due to the elimination of brittle microstructures.

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