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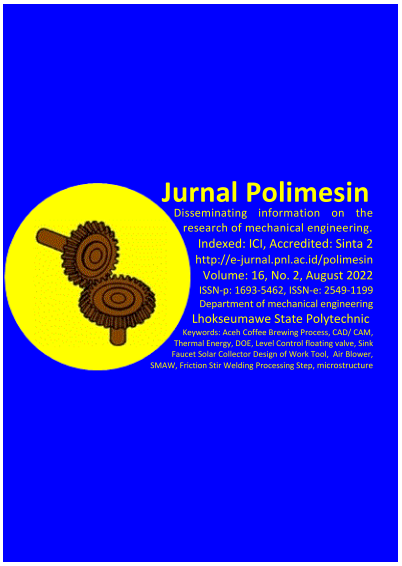

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CONTACT US:
Registration, submission, and LOA
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3D printing : Oil Treatment, Motor bensin, Viskositas, Aditif. Biodiesel CAD/CAE DOE Dissolved oxygen, geometry, microbubble, venturi-type generator, water-air flow rate FDM Field Snail Shells Heterogeneous Base Catalyst Multi-level dryer, uniform temperature, sharp turning channel. Nyamplung, used cooking oil, biodiesel, physical properties. Offshore crane, structure analysis, stress, fatigue, CAE. Optimization Propeller, COMSOL, CFD, Reaction Turbine Rotary friction welding, AISI 304, factorial, design of experiment, microstructure, tensile strength. TEC Tobacco Leaves, refrigeration system, PLC, SCADA Transesterification air conditioning cooling system, inverter, microcontroller technology, performance, real-time coconut fiber injection molding, RSM, ANN, optimization, model

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Politeknik Negeri Lhokseumawe
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Buketrata, Lhokseumawe, 24301, Aceh, Indonesia

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Evaluation of stress–relieving heat treatment on mechanical properties and microstructure of friction-welded JIS S45C steel

Alexander Eka Susanto[1], Gunawan Dwi Haryadi[1,*], Ismoyo Haryanto[1], Sulardjaka[1], Sri Nugroho[1], I Made Wicaksana Ekaputra[2]

[1]Department of Mechanical Engineering, University of Diponegoro, Semarang 50275, Indonesia

[2]Department of Mechanical Engineering, University of Sanata Dharma, Yogyakarta 55281, Indonesia

*Corresponding Author: gunawan_dh@ft.undip.ac.id

Abstract

This research evaluates the effect of stress-relieving Post-Weld Heat Treatment (PWHT) on the mechanical properties and microstructure of friction-welded JIS S45C steel joints. The PWHT was conducted at 500 °C for 1 hour. Tensile and Vickers microhardness tests were performed on both as-welded and heat-treated specimens. The tensile tests showed that fracture consistently occurred in the base metal, confirming good weld quality. Stress-relieved specimens showed a 3% increase in elongation compared to the as-welded condition, indicating improved plasticity. The Vickers microhardness tests revealed around 10% decrease in hardness at the weld center zone (from 293 HV to 267 HV) and heat-affected zone (from 245 HV to 224 HV) after treatment. Metallographic observation indicated coarsening of the pearlite phase due to thermal exposure.

Keywords:

JIS S45C, PWHT, rotary-friction welding, stress-relieving, Vickers micro-hardness

1 Introduction

Medium carbon steel is still widely applied to various mechanical products due to its appropriate properties and optional additional alloying elements [1]. One of the medium carbon steel grades produced by the Japanese Industrial Standard (JIS) is called JIS S45C because it has good welding properties, which is often used in the industrial world as a base material for machinery making, such as head suspension and crankshafts [2], [3]. Although it has good welding properties, JIS S45C has a higher carbon content, making it harder to weld, especially using fusion welding, because higher carbon steel exhibits increasing hardenability in the Heat-Affected Zone (HAZ). Therefore, solid–state welding, such as the friction welding method, was used [4].

Although friction welding has advantages, such as not requiring other materials (fillers) and being in a solid-state process, technical drawbacks were still found during the joining process [5]. Moreover, residual stress effects after the welding process were still found, although the effect was not as severe as that of the fusion welding method. The transformation of the microstructure of the surrounding area from the contact zone could still be found [6]. This microstructure transformation can generate residual stress that can affect the mechanical properties of the material [7]. Therefore, Post-Weld Heat Treatment (PWHT) is used to reduce the residual stress [8].

Several studies show that PWHT enhances or decreases specific properties of similar friction-welded joint materials. Trung et al. analyzed the effect of annealing PWHT at 650 °c with 4 hours of soaking time on the mechanical properties of joints AISI 1030. The PWHT can decrease the tensile strength and hardness value. The annealed weld has a tensile strength reduction of about 24% and a hardness reduction of nearly 20% compared to the original weld. The cause of the bad result is the increasing grain size and uniformity of the phase distribution [9]. Uhlenberg et al. also reported on the response of stress relieving PWHT on the fatigue strength of the friction welded joint of structural steel S355J2+N. The results show that the PWHT can reduce fatigue strength, decreasing the hardness [10]. Another research by Soomoro et al. reported the influence of full annealing on tensile strength, hardness, and the microstructure of rotary friction welded joint AISI 1018. Based on the outcome, the full annealing improves the ductility, but the tensile strength significantly decreases. The full annealing yielded a more equiaxed microstructure [11].

In the other case, Hong Ma et al. with friction welded joints of carbon steel AISI 1045 and stainless steel 304 for the dissimilar joint material. The results showed that chromium carbides such as (Cr, Fe) 7C3 and Cr7C3 were established in the weld zone. The quantity of the chromium carbides increased with the increase in temperature after the joint was given PWHT. That is the reason why the tensile strength of the joint decreases as the PWHT temperature increases [12] Almost similarly, the tensile and the hardness of RFW joint 32–2Mn to 40 – Cr – Ni were decreased if exposed to PWHT. From the proof, the PWHT joint exhibits a homogeneous microstructure [13].

Based on the literature review, research exists about stress-relieving PWHT on the friction-welded joint JIS S45C. This knowledge is fundamental to ensuring the removal of residual stress after welding and choosing the appropriate PWHT of friction-welded steel for safety and design purposes in this study. Therefore, this experiment will fill that gap.

This paper investigated the effect of PWHT by relieving treatment on the mechanical properties and microstructure of friction-welded joints of JIS S45C. The mechanical properties to be studied are tensile properties and the distribution of hardness. In addition, the connection between mechanical properties and characteristics of the microstructure will be analyzed.

2 Materials and experimental methods

2.1 JIS S45C

Commercial cylindrical JIS S45C carbon steel was used in this experiment. The as-received condition was hot-rolled with a diameter of 13 mm. Specification of chemical compositions and mechanical properties of the JIS S45C carbon steel with the condition as-received was listed respectively in Table 1. The typical microstructure of S45C carbon steel contains pearlite and ferrite.

Table 1. JIS S45C steel properties

Chemical compostions JIS S45C (wt.%)								
C	Si	Mn	P	S	Cr	Ni	Cu	B
0.44	0.27	0.64	0.015	0.014	0.34	0.09	0.02	0.0021

Mechanical properties of JIS S45C	
Property	Value
Tensile strength (MPa)	675
Yield strength (MPa)	420
Elongation (%)	22.5
Reduction of area (%)	42.0

2.2 Friction welding and PWHT

In this experiment, friction welding was carried out on the modified turning machine; the schematic of the modified turning machine can be seen in Fig. 1. This turning machine is equipped with a hydraulic pack system. The control unit is also attached to the hydraulic pack so that the welding parameters, like friction and forging pressure or time, can be controlled accurately. All of the welding parameters can be seen in Table 2.

After the welding process was done, the PWHT of stress-relieving treatment was conducted in the furnace. Stress-relieving was conducted at 500 °C with 60 minutes soaking times. After that, it was slowly cooled to room temperature. To ensure the inside of the furnace has a temperature of 500 °C, a thermocouple was inserted into the furnace.

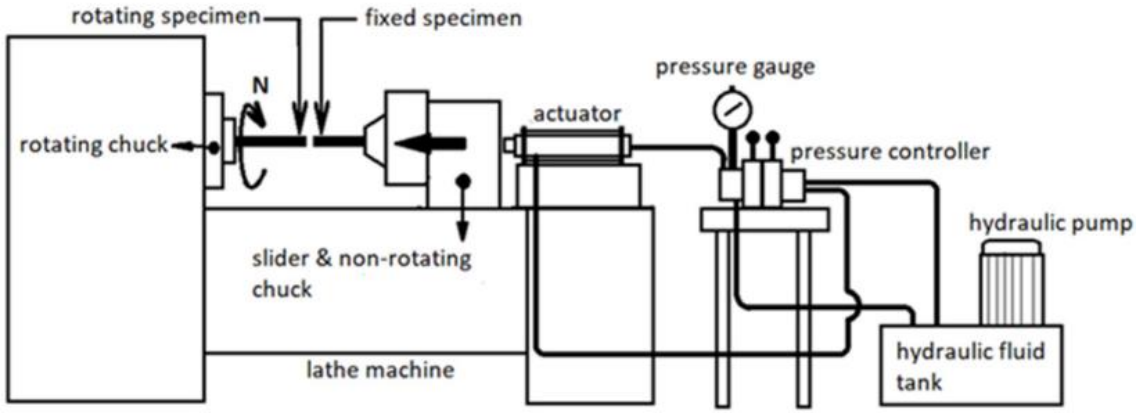


Fig. 1. Modified turning machine for RFW operation [15]

Table 2. Parameter for the RFW process

Process parameter	Value	Unit
Rotation (rpm)	1330	rpm
Friction pressure (Bar)	40	Bar
Friction time (s)	5	seconds
Forging pressure (Bar)	45	Bar
Forging time (s)	5	seconds

The specimen sample was ready for tensile testing and was machined with a CNC turning machine. Low rotation (700 rpm) and coolant are used during the turning process, with the expectation that no white layer will be formed on the surface that will affect the mechanical properties [14]. All of the samples were polished along the axis with sandpaper. The complete dimensions of tensile specimens can be seen in Fig. 2

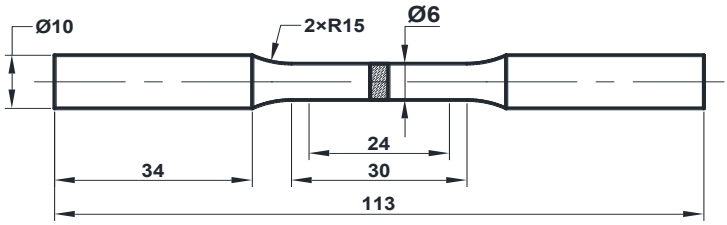


Fig. 2. Dimension specifications for tensile testing specimen (all in mm)

2.3 Microstructure observation and mechanical testing

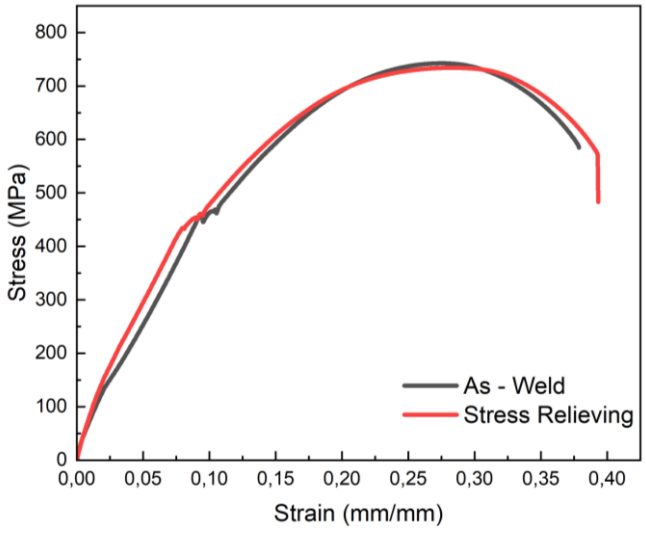
The sample was cut on the cross-section for the microstructural observations, and the procedures for microstructure observations were carried out on the ASTM E-407 standard. The cross-section sample is mounted with resin, then the surface is polished with sandpaper (#800, #1000, #1200) and metal paste for polishing. To reveal the grain on the microstructure, an etchant solution of nital 2% was used for 55 seconds at room temperature [16]. An optical microscope of the Metallurgy Union model was used to analyze the microstructural characterization.

A universal testing machine, 50 kN (JTM–UTC220 6604), was used to conduct tension tests to assess the mechanical properties and quality of the joints. The constant crosshead speeds are maintained at 2 mm/min [12]. All the tensile test procedures were performed according to ASTM E-8 standard [17]. The hardness distribution of friction-welded specimens was performed using a Vickers microhardness tester machine (Mitutoyo, HM-102). Following the instruction of ASTM E-384, 100 gf was applied to the longitudinal portion of the joints with dwelling periods of 15 seconds along the center line to measure the value of hardness distribution, with 0.1 mm spacing between indentations, and a total of indentation is 206 indentations for two specimens [18].

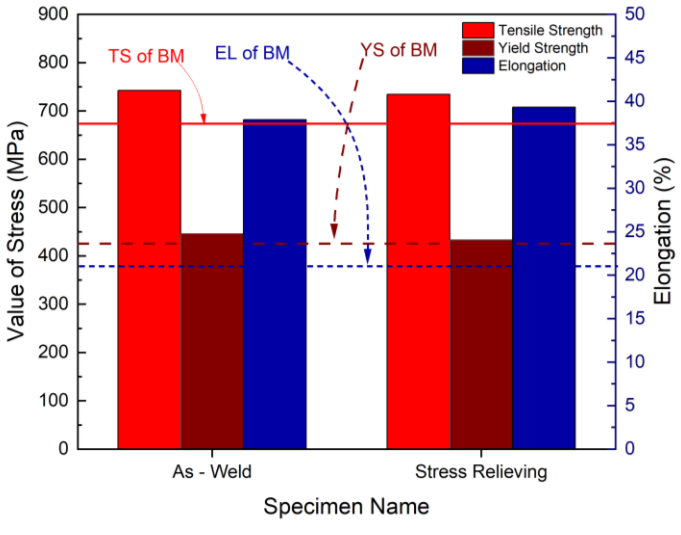
3 Results and discussion

3.1 Tensile characterization

Fig. 3(a) shows a typical curve of tensile test results for JIS S45C for as-welded and stress-relieving treatment specimens. Both specimens' tensile strength, yield strength, and elongation were compared and shown in Fig. 3(b). There is no significant difference in properties obtained from the tensile test. Yet, there is about a 3% improvement in plastic deformation for stress relieving treatment, longer than that of the as-welded. The tensile and yield strength for both as-welded and stress-relieving treatments show only below 1% differences. The tensile strength is around 730 MPa, and the yield strength is around 430 MPa. Compared to the base metal, the welded specimens' ultimate and tensile strength increased by around 40%.



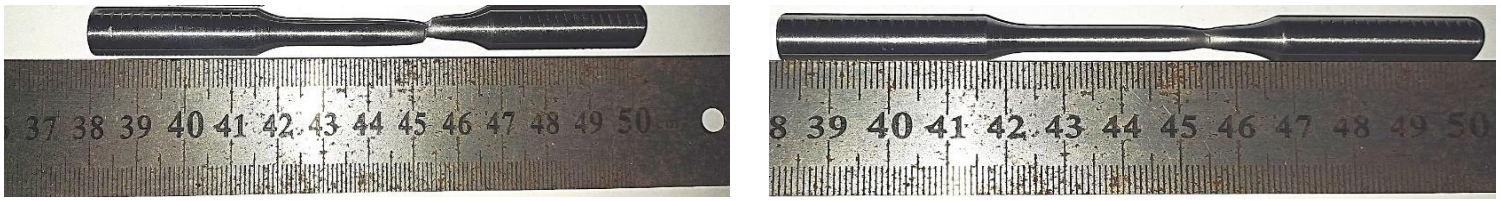
(a)



(b)

Fig. 3. Results of tensile testing JIS S45C, (a) stress–strain curve; (b) value of the tensile mechanical properties

The percentage of junction strength compared to the base metal is known as the welding efficiency. Therefore, it was computed as (as-weld joint or PWHT joint specimen tensile strength/base metal or as–weld joint tensile strength) × 100%. Comparing the tensile strength, the maximum RFW efficiency of as–weld specimens was 109.20%. On the other hand, the efficiency joint of the PWHT specimen was 108.78%. This drop value of PWHT specimen is also reported by Emre et. al [19]. Fig. 4 (a)-(b) exhibits the fractured tensile specimens. The fractured two types of joint specimens happened in base metal and were located far away from the joint, and it was ordinary ductile fractured cups and cones. From the value of joint efficiency and fractured photo, it can be concluded that it was a perfect joint value. Since the relieving treatment enhances the ductility, it means the machinability properties of the material have improved.



(a) (b)

Fig. 4. Fractured tensile testing specimens: (a) as–weld, and (b) stress relieving

3.2 Micro Hardness Characterization

The hardness distributions along the central line of the as–weld joint and the stress-relieving treatment joint specimen are illustrated in Fig. 5. In the as–weld joint, the Weld Center Zone (WCZ) exhibited greater hardness than the Thermo-Mechanically Affected Zone (TMAZ). The Heat-Affected Zone (HAZ) is likely due to grain refinement due to dynamic recrystallization on the interface. The hardness value decreased from the WCZ to the base metal, reaching a minimum value. The reduction in hardness of S45C carbon steel may be attributed to the elevated ferrite content in the TMAZ and HAZ. A slight difference in hardness between as-welded and stress-relieving treatment is observed at WCZ and HAZ. The hardness value for WCZ and HAZ of the as-welded is 299 HV and 238 HV, respectively. The hardness value for WCZ and HAZ of stress relieving treatment specimens is 270 HV and 214 HV, respectively. The hardness for stress-relieving treatment decreases by about 10% at WCZ and.HAZ. The distribution value is almost the same as the research conducted by Morisada et. al [4]

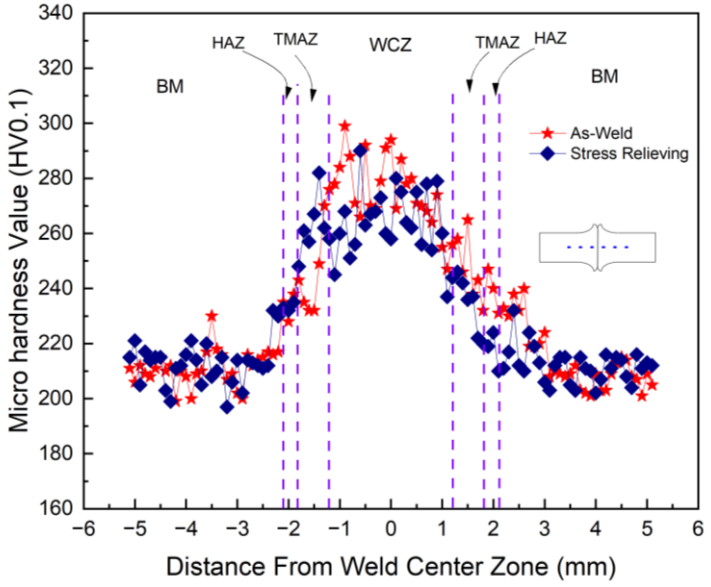


Fig. 5. The distribution of hardness values for each experimental specimen

3.3 Microstructure Characterization

Fig. 6 shows the longitudinal section of the friction–welded joint and the appearance of the carbon steel JIS S45C joint. The flash was perfectly formed during the welding process, and there were no welding defects, such as fractures or voids.

Several studies prove there is a difference in the microstructure of friction-welded joints [20], [21]. Figs. 7 and 8 show the microstructure of the as–weld joint and stress-relieving treatment specimens along the central carbon steel JIS S45C line. The zone can be categorized into four parts: WCZ, TMAZ, HAZ, and BM. Significant differences exist in the microstructure between the BM and WCZ. While the heat impacts the HAZ and does not undergo deformation, WCZ and TMAZ are thermomechanically impacted by deformation, leading to recrystallization or structural deformation [22]. As is ordinary for rotary friction welds, the thermomechanical action results in a dynamic recrystallization that produces a fine-grained microstructure [23].

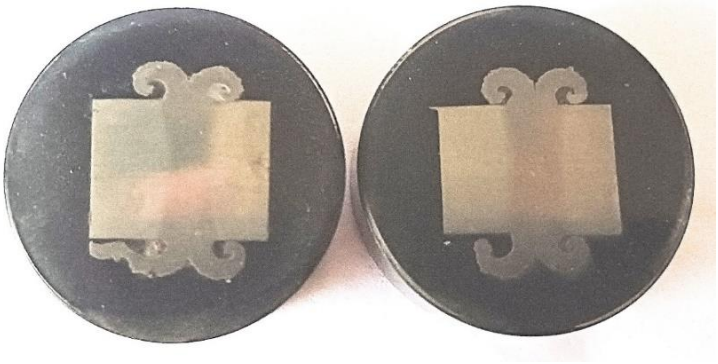


Fig. 6. Cross section of RFW joints JIS S45C, as–weld (left side); stress relieving (right side)

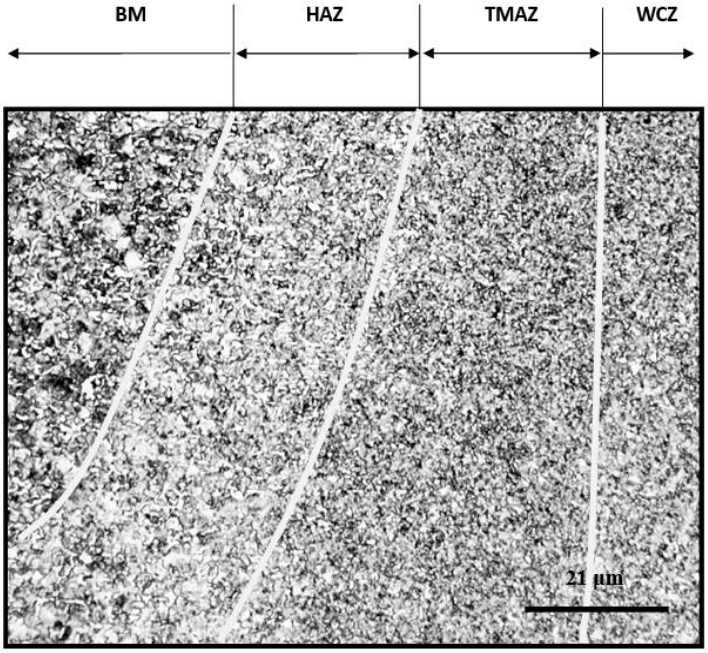


Fig. 7. The distribution microstructure of the as-welded specimen

The most significant quantity of pearlite in the WCZ area is observed. Also, the area fraction of pearlite in the WCZ section is more significant than that of the neighboring areas. This quantity of pearlite proves that it was previously transformed into austenite around the WCZ area. In addition, after slow cooling, it was fine pearlite in the emerging fine ferrite matrix grain, with the ferrite

grain size being ~1.45 µm. There is grain refinement in the WCZ area because of recrystallization, including the amount of plastic deformation from pressure. This phenomenon is also described by Morisada et al. [4] and Celik et al. [24].

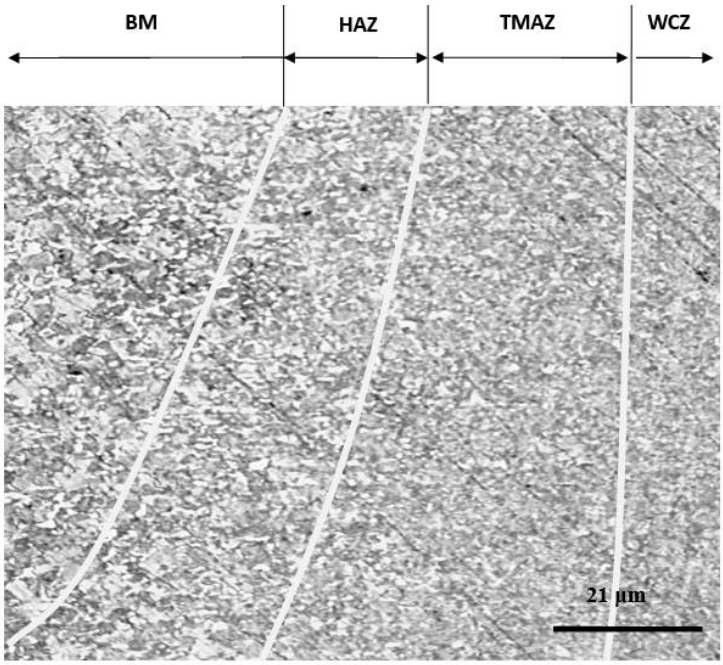


Fig. 8. The distribution microstructure of the PWHT specimen

On the other hand, getting further away from the WCZ area, more precisely in the TMAZ area, the pearlite becomes rougher and the ferrite grain size becomes larger than ferrite in the WCZ area. The transformation in pearlite size is due to heat exposure and the decrease in pressure. However, the only factor that affects the microstructure is the plastic deformation. Still, the pearlite colony looks finer than the colony of pearlite in the BM side [25]. The BM side consists of equiaxed grain microstructure. The ferrite grain size in the TMAZ side is ~7.6 µm, the HAZ side is ~9.6 µm, and on the BM is ~15.38 µm.

Compared to the as-welded phase, the stress-relieving phase shows a similar distribution of WCZ, TMAZ, HAZ, and BM. However, the size of the ferrite is slightly bigger than in the as-welded phase, because the stress relieving treatment only provides recrystallization. This recrystallization can reduce the dislocation density and lead to carbon segregation [26]. The bigger size of the stress-relieving phase proves that after stress-relieving treatment, the ductility increases and the hardness decreases. Also, this

4 Conclusion

This research demonstrated that stress-relieving treatment at 500 °C for 1 hour has a modest but measurable effect on friction-welded JIS S45C joints. The treatment slightly increased tensile ductility by approximately 3%, while reducing hardness in the weld center and heat-affected zones by around 10%. Microstructural analysis confirmed coarsening of the pearlite phase, correlating with the reduction in hardness and enhancement of ductility. These changes are beneficial for improving the machinability of the joint without compromising its structural integrity. To conclude, the results highlight the potential of stress-relieving PWHT and provide understanding the balance between strength and ductility in friction-welded components.

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