Tensile properties of the reclaimed steel rail flash butt joint

Anuar Pawan1,2, Zuraidah Salleh3*, Akid H Zulkefli3, Ya’kub Md Taib3, Anizahyati Alisibramulisi2,4 and Nik Roslin Masdek3

1 Public Works Department, Jalan Sultan Salahuddin, 50582 Kuala Lumpur, Malaysia
2 Faculty of Civil Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Malaysia
3 Faculty of Mechanical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Malaysia
4 Institute for Infrastructure Engineering and Sustainable Management (IIESM), Universiti Teknologi MARA, 40450 Shah Alam, Malaysia

corresponding author’s e-mail: a_kzue@yahoo.com*

Abstract. The development of the public transportation vehicles such as railway train had an incredible impact on the expansion of human mobility. In constructing the railways, quality assurance must be considered as it is very important to the project. The Malaysian Public Works Department (PWD) has undertaken the East Coast Line Track Rehabilitation Project between Gemas to Mentakab, which is estimated to cost RM220 million, these 123 km-long railway rehabilitation projects would use the reclaimed rails rather than the new rails. The reclaimed rail was manufactured according to the European standard EN 13674-1 and previously installed on site were examined and tested before could safely use in this track rehabilitation project. The reclaimed rails are analysed using ultrasonic inspection, hardness test, tensile test and micro examination to ascertain the safety values of mechanical properties such as tensile properties, hardness properties and microscopic morphology which regards to the composition of the welding joint and rail. Thus, to determine the reclaimed rails able to withstand forces applied on it without causing failure.

1. Introduction
The public transportation is a vital importance across many countries. The development of the public transportation vehicles such as railway train had an incredible impact on the expansion of human mobility. Railway line and its facilities are continuously improved to meet this transportation needs. Quality assurance during railway construction is very important for safe and timely completion of the project. With the development of high-speed and heavy-load railway, more stringent requirements are put forward for the comprehensive properties of steel rails [1]. As the demand for traffic increases, the railway company tends to operate railway at higher speeds carrying heavier loads, thus reliable damage tolerance design and effective maintenance methods must be established [2]. Malaysian Public Works Department (PWD) has undertaken the East Coast Line Railway Track Rehabilitation Project between Gemas to Mentakab, which is estimated to cost RM220 million and these 123 km-long railway rehabilitation projects would use the reclaimed rails rather than the new rails [3]. The UIC54 reclaimed rails were operational track material recovered from site. The rail is T-type flat bottom with 54.77 kg mass per meter, was manufactured and previously installed using Flash Butt Welding (FBW)
according to the European standard EN13674-1 [4]. Using reclaimed rails with existing welded joint requires understanding of weld strength performance as rail joint is the weakest link in the track. Welded joint has variation in material hardness and during operation, the differences in rail head level can cause distortion to wheel passage impacting additional forces onto track material [5].

One of the preferred jointing technique in railway construction is using Flash Butt Welding. FBW provides high productivity, cost effective and producing high quality welding [6]. A flash butt weld is performed either in production site or on-site using track mounted machinery equipped with high capacity transformers and hydraulic system. A typical Flash Butt Welding process is described in Figure 1 as follows:

![Diagram of Flash Butt Welding process](image)

**Figure 1.** Typical FBW welding cycles from initial burn-off, preheating, flashing and retraction [6]

FBW process number 1 to 3 in Figure 1 shows the welding process begins with fixed end of one rail is pressed with another rail’s end in the longitudinal direction. Then a clamping force is applied followed with high current passing through the clamps. The current heats up both rails causing both ends to melt and jointed as shown in Figure 1 (item 4)[6]. The rail feeding rate is programmed in between 0.1 to 2.5 mm/s and to ensure homogeneity of molten rail, a total length of 20 to 30 mm is consumed. Once desired length is obtained, the current is turned off and excess molten material will be shaved away using designated rail profile plate. Flash Butt Welding producing very high temperature in the fusion zone (FZ) and the heat affected zone (HAZ). These temperatures decrease rapidly as the distance from the fusion zone increases. This heating followed by cooling to ambient temperature produces stresses in the rail referred as residual stresses [7]. During railway operation, rails are subjected to temperature changes, cyclic loading, fatigue stress and inherent residual stresses might weaken the joints, thus pertinent investigation is required to ensure welded joints are in the good condition.

Thus, this study will determine the tensile properties, hardness properties and microscopic morphology which regards to the existing weld quality against base material experiencing the same operational
condition. Testing of rail sample is always following the relevant standards, regulations and legislations. The testing of rail welds is directly linked to the quality assurance of the railway.

2. Methodology
In this study, all specimens for tensile test, hardness test and metallographic analysis are taken from longitudinal section across the rail head as shown in Figure 2. For welded rail, the sample length is 260mm and covers several regions in longitudinal direction of the rail sample; base material (BM), heat affected zone (HAZ), fusion zone (FZ) and central line of weld (CL).

2.1. Sample preparations.
All specimens are inspected using ultrasonic inspection machine to ensure samples are defect-free from any cracks, flaws or internal material defects. The sample preparation processes involve band-saw cutting, face milling and precision surface grinding. These processes are selected to eliminate additional heat into material, to ensure repeatability process of producing precise dimensioning and consistent surface finishes. Final test piece shapes are carried out using water-jet cutting process for high precision cutting dimensioning and low temperature abrasive cutting process.

2.2. Tensile test.
The standard used in preparation of tensile specimen and the testing procedure is adhering to ASTM E8/E 8M for consistent and reliable results [8]. Rectangular tensile specimens from the base material (BM) and welded rail samples were machined to standard 50mm gauge length and 12.5mm width. Tensile tests were carried out at room temperature at nominal strain rate of 0.3mm/min. The Universal Testing Machine (UTM) model Instron 3382 with load up to 100kN was used for tensile test.

2.3. Hardness test.
For hardness test, the specimens are prepared and tested in accordance to EN 14587-1. For both base material and the welded rail sample, the hardness distribution was measured with impression on line traverse from the central line (CL) to point on each side of the weld point 20mm into the BM; unaffected parent rail with spacing of 2mm centres. Vickers hardness HV30 was used in determining the hardness distribution across the BM and welded rail sample. The hardness testing machine model Mitutoyo MVK-H1 were used for hardness test.

2.4. Microstructure analysis.
The microscopic morphology analysis was determined by conducting microscopic examination according to EN 14587-1. This requires additional sample preparations involve thermoplastic
mounting, polishing and etching. The analysis will examine the existence of the microstructures consisting of different sizes of ferrite, \( \alpha \)-Fe and pearlite, \( \alpha \)-Fe\(_2\)C from BM and welded rail and were observed from the micrographic analysis with a set number of magnifications. Microscope (Image Analyzer) Leica Q550 MW were used for microscopic examination.

3. Material properties
The type of reclaimed rail used in this study is rail profile UIC54 grade R900A. Table 1 shows the chemical composition and tensile properties of UIC54 grade R900A.

| C    | Mn    | Si    | Cr | S     | P     |
|------|-------|-------|----|-------|-------|
| 0.6-0.8 | 0.8-1.3 | 0.1-0.5 | -  | 0.04 max | 0.04 max |

The R900A rail has chemical composition (wt%) of 0.6-0.80 C, 0.8-1.3 Mn, 0.1-0.5 Si. This T-type section rail (flat bottom rails) with a 54.77 kg mass per meter with density of 7850 kg/m\(^3\). For a standard track, UIC54 rail is commonly used for medium and heavy load traffic [9,10].

4. Results and discussions

4.1 Tensile properties.
Tensile test specimens (ASTM E8/E 8M; Gage length: 50 mm, Width: 12.5 mm) are sampled from the head of the rail. The tensile shear test was conducted by using Universal Testing Machine (UTM) model Instron 3382 at room temperature with a constant nominal strain rate of 0.3 mm/min. Testing repeated for 3 samples of BM and welded rail. Comparison was made by observing the necking and fracture location on the specimens. Specimen J is unwelded and unaffected parent rail, hence the regions of CL, FZ and HAZ does not exist. Specimen K, L and M are rails joint by flash-butt welding.

In general, specimen K, L and M experienced similar tensile behaviour. By observing Figure 3, specimen J experienced necking at a region in between the gauge length. Fracture also occurred in the same region with a value of elongation. While, specimen K experienced necking at two location which is HAZ. For sample K, the necking does not exist in FZ region as shown in Figure 4.

A brittle material usually ruptures when the maximum tensile normal stress exceeds the ultimate tensile stress. Since the samples elastic and plastic deformation as observed in the non-linear curve, the specimens are considered as ductile material as Stress-Strain Diagram in Figure 5.
Table 2 represents the tensile properties of both BM and welded rail yields the maximum load, tensile strain and UTS undergoes by welded rails have significant difference which is lower than BM. Referring to the non-linear deformation curve region in Figure 5, all samples experienced to strain hardening and limited period of necking.

Only sample J experienced more necking and it was proven because sample J elongates with the value of 9.16 mm which is the greater value compared to other samples. Thus, base material is more ductile and lower brittleness rather than welded sample. It is also proven that the ductility of sample J is the greatest, refer Table 2. Hence, the application of FBW on the rail reduced the ductility and exhibits more brittle behaviour to the steel. Welded samples underwent FBW were decreased in the value of UTS, Young’s Modulus and ductility. The percentage of decrement were calculated, and Table 3 shows all the tensile properties of the rail sample were decreased by average of 25% from its nature after the application of FBW.

The UTS of the welded sample dropped by 24% compared to BM. This shows the tensile strength of the rail steel were reduced and the rail steel becomes weaker. Decrement in ductility value explains that the welded rail steel exhibit little plastic deformation compared to BM as recorded on stress-strain

Table 2. Tensile Properties

| Tensile Properties       | J     | K     | L     | M     |
|--------------------------|-------|-------|-------|-------|
| Maximum Load (kN)        | 46.04 | 35.72 | 34.79 | 35.34 |
| Tensile Strain (mm/mm)   | 16.07 | 11.16 | 11.37 | 11.13 |
| UTS (MPa)                | 1227.71 | 963.46 | 927.70 | 906.77 |
| Young’s Modulus (kN/mm)  | 18.48 | 16.31 | 17.11 | 16.12 |
| Elongation (mm)          | 9.16  | 6.36  | 6.48  | 7.44  |
| Ductility (%EL)          | 4.58  | 3.18  | 3.24  | 3.72  |

Table 3. Mechanical Properties of rail steel after FBW

| Tensile Properties       | Average value | Decrement Percentage (%) |
|--------------------------|---------------|--------------------------|
| UTS (MPa)                | 1227.71       | 932.64                   | 24.03 |
| Maximum Load (kN)        | 46.04         | 34.62                    | 10.66 |
| Young’s Modulus (kN/mm)  | 18.48         | 16.51                    | 26.20 |
| Ductility (%EL)          | 4.58          | 3.38                     | 24.80 |
curve in Figure 5. The limited plastic deformation on the specimen exhibits brittle material and can be observed on non-linear curve of sample K, L and M in Figure 5 is smaller than sample J. Generally, UIC54 has high uniform strain properties. Welded samples (K, L, M) have lower UTS value, less than 950 MPa compared to BM with UTS value of 1,227.7 MPa. The linear region shows the yield strength of the sample, BM have the highest yield strength compared to the welded sample. It can be stated that the tensile behaviour of UIC54 have been reduced from its nature if FBW is applied on the rail and HAZ is the weakest region on the track.

### 4.2 Hardness distribution

The micro-hardness analysis was performed by using hardness testing machine model Mitutoyo MVK-H1 and comply to standard EN 14587-1. Hardness impressions were taken on a line 3-5mm below the running surface on the vertical longitudinal axis of the rail with spacing of 2mm between the points. An average of three readings at each location was recorded;

![Hardness Distribution](image6.png)

**Figure 6.** Hardness Distribution across the rail.

The hardness values are found distribute differently across the rail profile. The hardness vs. distance graph in Figure 6 is the typical trend of the welding hardness analysis [11,12]. Observing the hardness values in FZ, the hardness value is high in this region and decreasing when entering the HAZ. FZ region recorded the peak of the hardness which can relate to the tensile behaviour, where FZ resists the occurrence of the necking due to its high-hardness thus, fracture does not occur in FZ. As the hardness recorded traverse from CL, the reading is decreasing but, a significant increment shown from HAZ to BM thus, BM have high value of hardness compared to HAZ.

It can be stated that, after FBW process, the change in temperature and microstructure would alter the hardness behaviour of rail in FZ. However, hardness in HAZ is affected by the internal stresses during the cooling process. Rapid temperature drop causing reduction in hardness values similarly experience with accelerated cooling by means of blowing compressed air to the weld section. Further, at both sides of the HAZ, hardness is reduced; therefore, these zones are called the softened zone [13].

### 4.3 Microscopic Examination

The microstructure analysis was performed by using Microscope (Image Analyzer) Leica Q550 MW and comply to standard EN 14587-1. The etching agent used have the following chemical composition per 10 litres; 1.875kg CuCl₂ – 2H₂O, 5 litres HCl-1, 18ml - 35%, 4.2 litres distilled water. The same etching agent used for both BM and welded rail samples. Figure 7 to Figure 10 show the
microstructures consisting of different amount and size of ferrite, α-Fe and pearlite, α-Fe₃C. The pearlite microstructure exists as dark grains within each grain the layers are oriented in essentially same direction, which varies from one grain colony to another. The light constituents are the ferrite phase. Pearlite has properties intermediate between those of the soft, ductile ferrite and the hard, brittle cementite. Mechanically, pearlite is harder and stronger than ferrite microstructure [14].

It is observed in Figure 7 that the micro-graph of CL has higher volume fraction of dark grains which is pearlite and limited light ferrite constituents. Thus, the CL region represents the behaviour of high hardness and strength properties. Figure 8 indicates the FZ with significant amount of ferrite and pearlite region as CL but coarser grain size. Coarse grain size associates with the low grain boundaries that acts as a barrier towards dislocation motion resulting the atoms in the grain will easily slides past one another [14]. Therefore, coarser grain size associates with hard, strong yet brittle. Fine grains of ferrite and pearlite can be seen in HAZ region as shown in Figure 9. Higher volume fraction of white constituent is observed represents a larger amount of ferrite microstructure. Mechanically, ferrite has properties of soft and ductile [14].
The R900A rail used in this study has chemical composition (wt%) of 0.6-0.80 carbon, C which is in the range of steel, refer to Figure 11. Composition of 0.6-0.80 wt% C is between of the eutectoid-steel composition (0.76 wt% C) is consists only pearlite and ferrite. Therefore, high amount of ferrite in HAZ resulting the weak and soft behaviour but, high in ductility [14]. In the weld section, there are two distinctive regions. One is the region where the rail material is heated completely up to an austenite temperature region (dark part) by welding, and the other is the region where the rail material is heated to above the A1 point (approximately 727°C) and to a two-phase region (white part) that exists on both sides of the above-mentioned region. These two regions are collectively termed as the FZ and HAZ [13]. The occurrence of necking in HAZ values as discussed in tensile properties is due to the high ductility in HAZ region which allows the specimen to experience strain-hardening deformation in the non-linear deformation curve as shown in Figure 4.

5. Conclusion
The tensile properties of reclaimed rail joints were determined with the several testing conducted in purpose of relating the hardness properties and microstructure morphology. Following conclusions can be drawn from the investigations:

- The necking occurred in HAZ region when a uniaxial load is applied indicates the inherent of internal stresses when the rail was cooled to the ambient temperature right after the welding process. Under tensile stress, the material breaks within HAZ region and the necking occurred on both sides from the CL. The elongation, %EL experience by base material is higher compared to welded rail indicates the HAZ has intermediate ductility properties even it is soft and weak.
- Low hardness value exhibits in the HAZ region showing the properties of soft and weak yet ductile.
- Microstructure analysis shown that higher volume fraction of white constituent (larger amount of ferrite microstructure) exists in HAZ region, indicates the weak and soft properties of ferrite in HAZ region.
- BM has greater values of UTS, Young’s modulus and ductility compared to HAZ due to microstructure alteration from welding process.

6. References
[1] D X Li 2005 Analysis of causes for rail breaking and preventative measures, Railway Stand Des 3 pp 67–69.
[2] Y D Li, C B Liu, N Xu, X F Wu, W M Guo and J B Shi 2013 A failure study of the railway rail serviced for heavy cargo, Case Studies in Engineering Failure Analysis 1, pp 243–248.

[3] The Sun 2017 Public Transport Initiative Available at https://www.pressreader.com/ [Accessed: 9-September-2017].

[4] British Standard Institution 2011 BS EN 13674-1:2011 Railway Applications - Track - Rail - Part 1: Vignole Railway Rails 46 kg/m and above Available at: http://www.standardsuk.com/ [Accessed: 02-May-2018].

[5] S Chandra and M Agarwal 2007 Railway Engineering, (London: Oxford University Press), pp 294-311.

[6] K Saita, K Karimine and M Ueda 2013 Trends in Rail Welding Technologies and Our Future Approach, Nippon Steel & Sumitomo Metal, (Japan: UDC) pp 84–92

[7] G H Little and A G Kamtekar 1998 The effect of thermal properties and weld efficiency on transient temperatures during welding, Computers & Structures, 68:1–3, pp 157–165.

[8] American Society for Testing and Materials 2016 ASTM E8 / E8M-16a Standard Test Methods for Tension Testing of Metallic Materials Available at https://www.astm.org/ [Accessed: 17-Jun-2017]

[9] ArcelorMittal Europe: Long-Products - Rails & special section, 54E1 (UIC54) Rail” [Online] Available: http://rails.arcelormittal.com/ [Accessed: 02-May-2018].

[10] British Standard Institution 2009 BS EN14587-2 Railway application - Track- Flash butt welding of rails Railway applications. Infrastructure. Flash butt welding of new rails. R220, R260, R260Mn, R320Cr, R350HT, R350LHT, R370CrHT and R400HT grade rails in a fixed plant Available at: http://www.standardsuk.com/ [Accessed: 02-May-2018].

[11] F A Ghazali, Z Salleh, K M Hyie, Y M Taib and N M Nik Rozlin 2017 Improvement of Mechanical Properties and Fatigue Failure of Spot-Welded Joint through Pneumatic Impact Treatment (PIT), Pertanika J. Science. & Technology. 25 (S), pp 105 - 114

[12] Z Salleh, Y H P Manurung, Y M Taib 2018 Improvement of Mechanical Properties in Treated Spot Welded Joint, Journal of Mechanical Engineering, 5(6), (2018) pp 239-247

[13] K Saita, K Karimine and M Ueda 2013 Trends in Rail Welding Technologies and Our Future Approach, Nippon Steel & Sumitomo Metal, Japan UDC, pp. 84–92

[14] W D Callister and D G Rethwisch 2014 Material Science and Engineering, 9th edition, ISBN: 978-1-118-31922-2. (New York: Wiley–Interscience)

Acknowledgements
The authors gratefully appreciate the office of Public Works Department Malaysia, Ministry of Transport and Hikmat Asia Sdn Bhd, for their support in this railway material research project under Industrial Collaboration Program (ICP) for Gemas-Mentakab Track Rehabilitation Project managed by Technology Depository Agency Berhad (TDA Berhad). Technical and financial assistance provided by the Universiti Teknologi MARA (UiTM), in particular; Institute of Graduate Studies (IGS Support Fund), Faculty of Civil Engineering and Faculty of Mechanical Engineering are highly appreciated.