Fatigue life investigation of UIC 54 rail profile for high speed rail

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Abstract. This study is to investigate the fatigue life of high speed rail in Malaysia. This paper describes about the experimental and simulation analysis investigation on fatigue life of rail profile UIC 54 using bulk specimen according to ASTM E 466-15 standard. The Fatigue life testing was performed in the fatigue testing machine (Instron 8800) 100 kN. Meanwhile, the fatigue life analysis was performed in ANSYS Workbench 14.5. Furthermore, the stress levels for experimental testing were applied as 16.7%, 25%, 35%, 50%, 58.3%, 66.77% and 75% with machine frequency of 20 Hz. Apart from that, the total fatigue life cycles for rail profile UIC 54 were acquired from both experimental and simulation. The fatigue life S-N curves were plotted and validated with the results of the simulation analysis with experimental results.

1. Introduction

High speed railway is one of the primary advancement patterns to enhance the rail line transport capacity in recent years throughout the world [1]. Expanding requests for transportation items and travellers cause a quick progress in the transportation industry and railway vehicles are not avoided form this advance. The fatigue of high speed rail, it is important to find the endurance limit and the fatigue life cycle of rail steel. A lot of factors can contribute to fatigue life of railway material. Due to the long travelling distance and duration of high-speed trains running at high speed, structural materials of trains and track may change, and a wide range of shrouded issues be progressively uncovered, which may undermine security [2]. Fatigue failure is the failure of repeated or fluctuating stresses having high value, but below the ultimate strength of the material. The final fracture may have characteristics of brittle or ductile material, depends on the type of metal, stress apply and surrounding conditions. It is dangerous because it happened without any sign. The direction of applied stress is perpendicular to the surface of fatigue failure. Fatigue failure has three stages for rail steel that are initiation, propagation and final rupture as shown in figure 1. Initiation stage is the most complex stage and the irreversible changes in metal because of repetition of shear stresses. The initiation stage is quite small and not propagating more than two to five grains around the origin. Environmental condition, stress, metallurgical and strength conditions can be factors that affect crack on the surface. Site of stage 1 crack which is chosen for “fatal” crack is constantly competitive amid the distinctive times of loading [3]. Crack Propagation is stage 2 of fatigue failure. Micro structure start to change direction and develop perpendicular to the tensile stress. It is mostly prompt identifiable region of fatigue failure at this stage. The third stage is material rupture. The cross-sectional area of the part is
decreasing when the propagation of fatigue crack continues, become weakened greatly and the fracture can occur completely with the application of only one more load. The fracture mode is whether ductile or brittle or the combination of both, depends on the metal, stress level and environment [4].

2. Rolling Contact Fatigue (RFC)
Rail defects because of rolling contact fatigue (RCF) undermine the activity security around the globe. That danger is more unmistakable on railways without sufficient maintenance technique [5]. It also will cause the increment of contact stress at the wheel/rail and wear decrement of rail steel. Rolling contact fatigue (RCF) is a phenomenon which occurs because of overemphasizing of material by a large number of contact cycles between wheel and rail. It is represented by initiation and propagation of cracks under Hertzian contact stress that will grow on surface amid contact of the system of rail and wheel. The complex stress state at growing crack’s tip result from the contact stress may be overlaid by residual stresses. Moreover, Bending of the axle and thermal stress will lead to the normal stress between wheel/rail contact regions [6]. Rolling contact fatigue is one of the problems in high speed railway. Fatigue happens to rail steel when the stress is over a specific level and when the quantity of traffic loading cycles is sufficiently high [7]. Crack development of rolling contact fatigue is difficult to predict and depends on various aspects. Consequently, it is important to early recognize rolling contact fatigue defects [5]. Furthermore, excessive wear of the rail head and decrease of rail life is due to the speed increment of the railway. The RCF brought on mishaps may not just aim individual injuries and economical costs, they may likewise tend individuals to commute by car, which rise traffic jam, causes ecological issues and in the end may prompt an expansion in individual injuries since car traffic is essentially more risky than railroad transportation [8].

3. Materials and Methods
The materials which were tested are UIC 54 profile, which meets the requirements of the Codex standard. The technical condition of manufacture and delivery of railway rails was standardized in Codex UIC 54 of the International Railroad Union and which has been harmonized with the world trends [9]. Furthermore, the UIC 54 rail profile provided by Malaysian Railway Assets Corporation (RAC) and the chemical composition material range is given in table 1. Moreover, rail profile is made from steel, graded according to ultimate tensile strength (UTS) and designated according to their weight per unit length (kilogram per meter). The UIC 54 rail profile was made for Malaysia high speed train (ETS) with weight scale of 54 kg/m. The fatigue life tests were conducted with Instron 8800 fatigue machine at a laboratory room temperature. In addition, the surface of the bulk specimen was polished in order to avoid improvement of the fatigue performance by delaying crack initiation and remove possible machining imperfections. The fatigue tests were executed with machine frequency of 20 Hz with a constant stress ratio of $R = 0.1$ for all 7 sets of the specimen [10]. Along with this, the fatigue limit were set as the maximum stress the specimen can withstand after 10E5
cycles without failure. The fatigue S-N curve was determined with variable applied stress level for 7 sets of the specimen such as 16.7%, 25%, 35%, 50%, 58%, 66.7% and 75% (Figure 2). Moreover, the specimen was mounted onto Instron 8800 fatigue testing machine with clamping at both ends and similar procedure for all specimens (figure 3 and figure 4).

**Table 1:** Chemical composition and mechanical properties of UIC 54 profile [6]

| Quality | Chemical composition (%) | Tensile strength (MPa) | Yield strength (MPa) |
|---------|--------------------------|------------------------|----------------------|
|         | C  Si  Mn  P  S  Cr  Ni  |                        |                      |
|         | (max) (max)              |                        |                      |
| Grade 900 A (UIC 54) | 0.6- 0.1- 0.8- 0.04 0.04 _ _ | 924                     | 533                  |
|         | 0.8 0.5 1.3             |                        |                      |

**Figure 2:** Bulk specimen technical drawing

**Figure 3:** Bulk specimen extracted from UIC 54 profile head region
4. Results and Discussion

4.1 Fatigue life Experimental Testing

In railways service, the rail steel parts subjected to repetitive or cyclic stresses will fail due to the fatigue loading. The UIC 54 profile structural damages occur even when the experienced stress range is far below the static material strength. In most cases, the failure of railway structures experienced sudden failure from fatigue loading. Furthermore, the testing was conducted with the variable stress level and constant stress ratio 0.1 (table 2). In addition, the applied stress level for fatigue life testing vary 16.7% to 75% and this is below the value of UTS, 924MPa of UIC 54 profile.

| Specimen | Stress level % | Stress max (kN) | Stress min (kN) | Stress ratio | Ramp (kN) | Amplitude (kN) |
|----------|----------------|----------------|----------------|--------------|-----------|----------------|
| 1        | 16.7           | 9.258          | 0.926          | 0.1          | 5.092     | 8.333          |
| 2        | 25.0           | 13.860         | 1.386          | 0.1          | 7.623     | 12.474         |
| 3        | 35.0           | 19.404         | 1.940          | 0.1          | 10.672    | 17.464         |
| 4        | 50             | 27.720         | 2.772          | 0.1          | 15.246    | 24.948         |
| 5        | 58.3           | 32.322         | 3.232          | 0.1          | 17.777    | 29.089         |
| 6        | 66.7           | 36.978         | 3.698          | 0.1          | 20.338    | 33.281         |
| 7        | 75             | 41.580         | 4.158          | 0.1          | 22.869    | 37.422         |

Apart from that, the fatigue life S–N curve for UIC 54 rail profile was successfully acquired as shown in figure 5. The fatigue life S-N curve is in relation to stress amplitude, S against the number of cycles, N.
of cycles, N. From the result, the UIC 54 profile loading condition was determined. Therefore, the UIC 54 profile fail in loading condition exceeds above the fatigue S–N curve and any loading condition below the S–N curve will be safe. The fatigue life testing result shows, for the maximum applied stress 639MPa (75% stress level from UTS) the fatigue cycle number was smaller (8000 cycles). As expected the result of fatigue life testing for UIC 54 profile was shown in the trend of i.e. at the smaller number of fatigue cycle with high stress amplitude. In the fatigue life S–N curve result, the endurance limit was obtained for UIC 54 profile. Based on the result, if the loading condition is lower than fatigue endurance limit of UIC 54 profile, the rail part will never fail due to fatigue for an infinite number of cycles. Subsequently, for the loading condition intercept with the endurance limit at S–N curve the rail part able to survive the failure. Furthermore, the fatigue endurance limit was determined for rail steel at lowest stress level with non-failure occurs.

![Figure 5: Fatigue life performance of UIC 54 profile](image)

In general, there are two regimen of fatigue cycle which are high cycle fatigue (HCF), N > 10E5 and low cycle fatigue (LCF), N < 10E4 or 10E5. From the results plotted on figure 5, the stress level 75%, 66.7% and 58.3% LCF meanwhile for stress level 50%, 35%, 25% and 16.7% HCF region. Moreover, for HCF the stresses are low enough that the stress–strain relation can be considered elastic. The high nominal strength of the rail steel (924 MPa) acts in favor of the very good HCF performance assisting late crack initiation. The carbon content of 0.6–0.8 wt% seems to have a beneficial influence by moderately assisting the ductility and fatigue performance. Meanwhile, the carbon content of UIC 54 profile shows with strength of material but reduced fatigue strengths. From the observation on failure bulk specimen, the crack propagation zone was at the middle of the specimen and this because of the principle load applied normal to the crack plane to open the crack (figure 6).
4.2 Fatigue life Analysis

The fatigue life analysis was executed with a bulk specimen model on ANSYS Workbench 14.5. Furthermore, this analysis was run with exact stress level value as used in fatigue experimental testing. The analysis result was used to validate the fatigue life experimental testing result and to observe the fatigue life gradient during testing. Table 4 tabulates the result of fatigue life analysis for bulk specimen model. From the fatigue life gradient result (figure 7), the affected stress region of bulk specimen was observed and predicts the UIC 54 profile fatigue life pattern whenever the load is applied. Based on the result, the maximum stress is subjected to the middle of the bulk specimen.

| Stress level (%) | Stress (MPa) | Total Number of cycles |
|------------------|--------------|------------------------|
| 50               | 462          | 16521                  |
| 58.3             | 538.692      | 9786                   |
| 66.77            | 616.9548     | 6455                   |
| 75               | 693          | 4492                   |

Figure 6: Failure bulk specimen
Figure 7: Fatigue life gradient for maximum stress level at 75 % (693 MPa)

The fatigue S-N curve for experimental and analysis testing was plotted in figure 8. From the result, the fatigue life performance for UIC 54 profile was validated with experimental and simulation testing. Furthermore, the curve pattern between experimental and simulation results was acquired in range and the material fatigue endurance limit was identified. The high cycle fatigue performance of this rail steel is consumed in a narrow range of 230 MPa between 693 MPa and 463 MPa. From the finding, the recommended applied stress level for the rail steel is below endurance limit, to have an infinite life cycle. The result illustrated, at the stress amplitude of 616.3MPa, the intercept between experimental and simulation results. Therefore, the number of fatigue cycle for UIC 54 profile was obtained similar at HCF regions.

Figure 8: Fatigue life prediction for UIC 54 profile
5. Conclusion

From the fatigue life testing, the endurance limit for UIC 54 profile was obtained. From the finding, the lowest stress amplitude for infinite number of cycle was identified for UIC 54 profile head region. Furthermore, from fatigue S–N curve the fatigue life performance of Malaysia high speed train rail was acquired. This result will be significant for KTM for selecting the high fatigue life performance rail for ETS and to calculate the life span of UIC 54 profile with number of the fatigue cycle to failure. The carbon content of 0.6–0.8 wt% seems to have a beneficial influence by moderately assisting the ductility and fatigue performance for UIC 54 profile. Whereas, the higher carbon content steel of UIC 54 profile shows higher strength properties but lower fatigue strengths [6].

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