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The Relationship between Fatigue Crack Growth and Residual Stress in Rails

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Abstract**—**Residual stress and fatigue crack growth rates are important to determine mechanical behavior of rails. This study aims to make relationship between residual stress and fatigue crack growth values in rails. For this purpose, three R260 quality rails (0.6-0.8% C, 0.6-1.25 Mn) were chosen. Residual stress of samples was measured by cutting method that is related in railway standard. Then samples were machined for fatigue crack growth test and analyze was completed according to the ASTM E647 standard which gives information about parameters of rails for this test. Microstructure characterizations were examined by Light Optic Microscope (LOM). The results showed that residual stress change with fatigue crack growth rate. The sample has highest residual stress exhibits highest crack growth rate and pearlitic structure can be seen clearly for all samples by microstructure analyze.

Keywords**—**Residual stress, fatigue crack growth, R260, LOM, ASTM E647.

I. INTRODUCTION

RESIDUAL stress is an interaction between deformation and microstructure. Especially, residual stress is found in complex parts. The relationship between residual stress and fatigue crack growth rate is important in failure mechanism. Residual stresses (tensile and compression) are locked in stress structure in metals. So, residual stress is important to determine tensile strength, hardness, stiffness, toughness and fatigue behavior. Therefore, fatigue crack growth rate is associated with residual stress. Fracture mechanism depends on fatigue crack growth rate. Fatigue life and material strength became important under variable loading and overloading area. Fatigue life depends on impurity, notch, crack type besides residual stress. Crack type details and fatigue precracking requirements were determined by specimen. With the help of notch, crack is initialed and fatigue crack growth rate is evaluated. Crack tip controls fracture and fatigue crack growth [1]-[4].

Residual stresses act a great role for fatigue of engineering materials. Because fatigue cracks generally initiate on surfaces. Cracks on surface due to residual stresses are generally highly appropriate for this event. Compressive stress is generally preffered rather than tensile stress. It is known that especially compressive residual stresses make a positive effect on fatigue life, fracture strength and stress corrosion. Compressive stresses prevent fatigue crack occuring and develeopment. Tensile stresses are harmful because they help cracks occur and develop. Besides, in terms of finding out the failure cause, it is important to know residual stress condition of tensile strength part [5].

Almost all produced parts have residual stresses caused by a production. These stresses are caused by a complex compounding of meterial, processing procedure, montage and action during service are not easily estimated. However, when they come together with service loads, they can cause extreme defects that cause breaking of the material.

Thermodynamic beahviour of meterial, external forces applied to the meterial, interaction between thermal and mechanical forces and structural transformations of the metal should be known in order to estimate residual stresses. Unless stress distribution of meterials that are exposed to plastic deformation are uniform, residual stresses will be always produced [6], [7].

Many researches were carried out in order to improve mechanic behavior and fatigue life [8]-[11]. It was reported that the effect of residual stress on fatigue behavior of Al alloys [8]. One study reported fatigue crack growth and role of residual stress. This study shows that the absence of residual stress makes the crack propagate [9]. Another research was carried out about residual stress and crack growth properties in Ti alloy. Fatigue crack growth test was applied and residual stresses were measured after laser peening process. However, crack growth rate decreased with the increase of compressive residual stresses in the crack growth direction [10]. Another study was about characterization of mechanical properties, crack initialing and residual stress [11].

This study focuses on the influence of residual stress on fatigue crack growth. For this purpose, residual stress of rails was measured than fatigue crack growth test was performed.

II. EXPERIMENTAL

Chemical composition of rails used in this study is given in Table I.

TABLE I
CHEMICAL COMPOSITION OF INVESTIGATED RAIL

Rail	%						Ppm	
	C	Si	Mn	P	Cr	V	O	H
R260	0.7	0.15	0.9	0.01	0.08	0.1	10	2

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Three rails with same casting number were used. Firstly, residual stress of samples was measured then, hardness, microstructure analysis and fatigue crack growth test were performed respectively.

A. Residual Stress

Residual stress measurement of three samples was performed by cutting method which is related in railway standard. Residual stresses were estimated by first attaching an electrical strain gauge on the rails foot surface. The strain gauge was located at the centre of the 1 m length of the samples. Surface preparing process was done with care in order not to change of the residual stresses in the rail foot before strain gauge was glued on rails foot. Then cutting process was applied.

B. Hardness

Brinell hardness test was carried out with 187.5 kg load to nine regions of head parts, as shown in Fig. 1, for all rails.

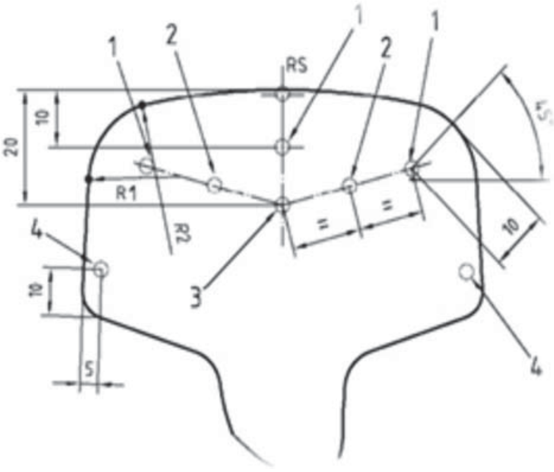


Fig. 1 Hardness measurement points [4]

C. Microstructure Characterization

The microstructures were analyzed by LOM. Before the microstructure analysis, samples were mechanically ground with 60, 120, 180, 240, 400, 600, 800, 1000,1200 grit emery papers followed by polishing with 6 µm and 1 µm diamond paste. Polished samples etched with nital solutions (nitric acid and alcohol). Head surfaces of rails were only examined after metallographic process.

D. XRD Analysis

XRD analysis is a unique method in determination of crystallinity of a compound. Rigaku XRD analysis machine was used determined for chemical compound, crystalline species and lattice parameters.

E. Fatigue Crack Growth

Fatigue crack growth contains cycle loading sample and make up precrack in fatigue. According to ASTM E647 samples are prepared. Moreover, crack-tip, force ratio, stress intensity factor are significant for this test method [1].

SE(B) sample and MTS Landmark Servo Hydraulic 100kN Dynamic Test Machine and displacement gage were used. SE(B) sample is common, particularly in fatigue. Crack growth depends on not only applied stress but also crack shape [3].

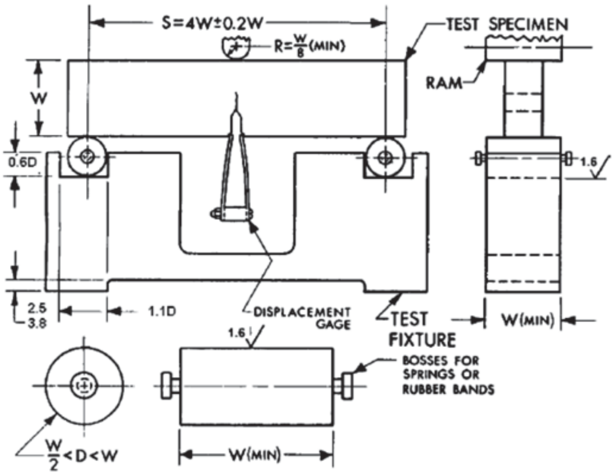


Fig. 2 SE(B) Sample and bend specimen [2]

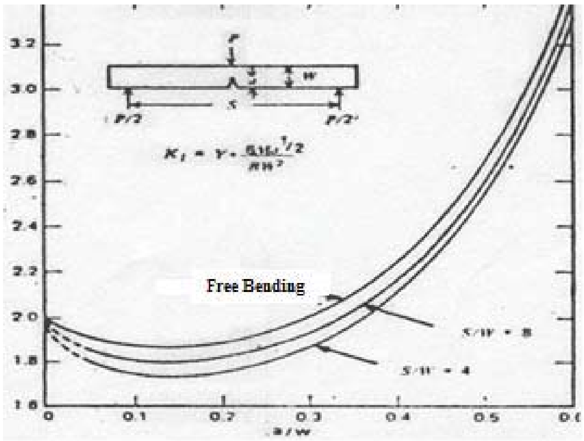


Fig. 3 The relationship SE(B) between relative crack length (a/w) [2]

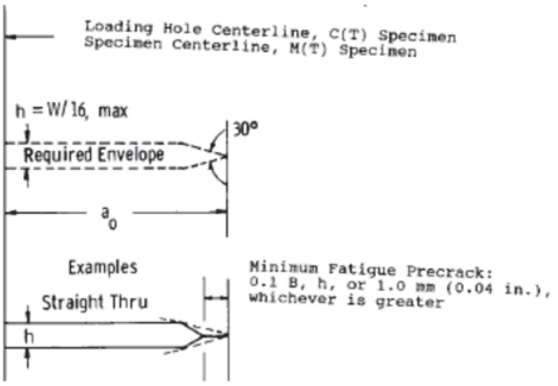


Fig. 4 Notch details and Requirement of Minimum Fatigue Precracking [2]

Precracks were created by exposing the samples to standard loads at room temperature using 3-point bending device before fatigue crack growth rate tests [1].

The conditions which are given as below must occur for the realization of the test. These ones;

- 0.45W<a<0.55W (W=2a)
- $1 \leq \frac{W}{B} \leq 4$ (B=0.5W)
- $R = \frac{Pmin}{Pmax}$ and $-1 < R < 0.1$

Parameters of the precrack and fatigue crack growth rate tests are given in Table II [1]-[3].

TABLE II
PARAMETERS OF THE PRECRACK AND FATIGUE CRACK GROWTH RATE TESTS

	Precrack	**Fatigue crack growth rate test**
Stress intensity level	15 MPa√m	8-15 MPa√m
Loading rate	0.5	0.5
Frequency	40 Hz	40 Hz
Distance between supports	180 mm	180 mm

The obtained values must be lower than 1.7×10^{-5} mm/Cycle for ΔK=10 MPa√m and also the values must be lower than 5.5×10^{-5} mm/Cycle for ΔK=13.5 MPa√m according to the TS EN 13674-1 standard [1]-[3].

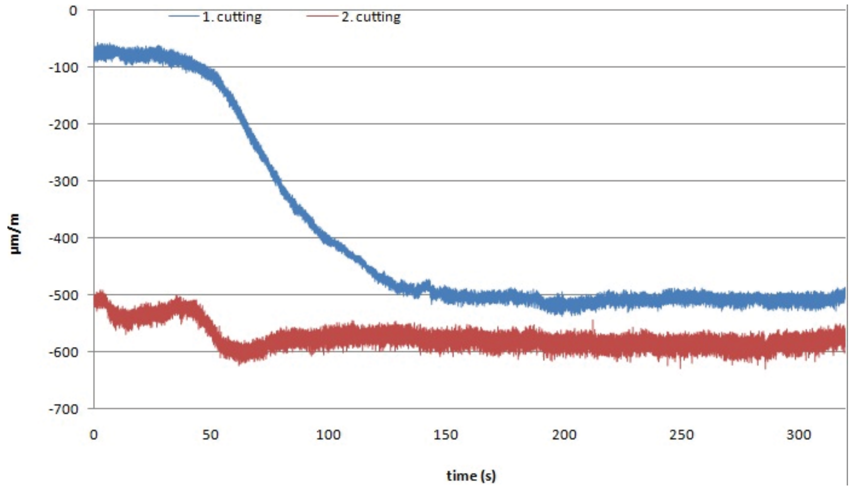


Fig. 5 Sample 1 (µm /m) / time(s)

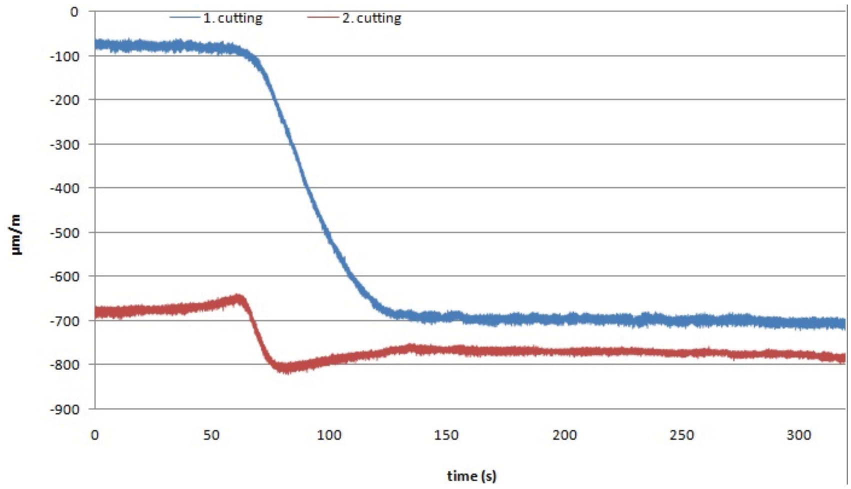


Fig. 6 Sample 2 (µm /m) / time (s)

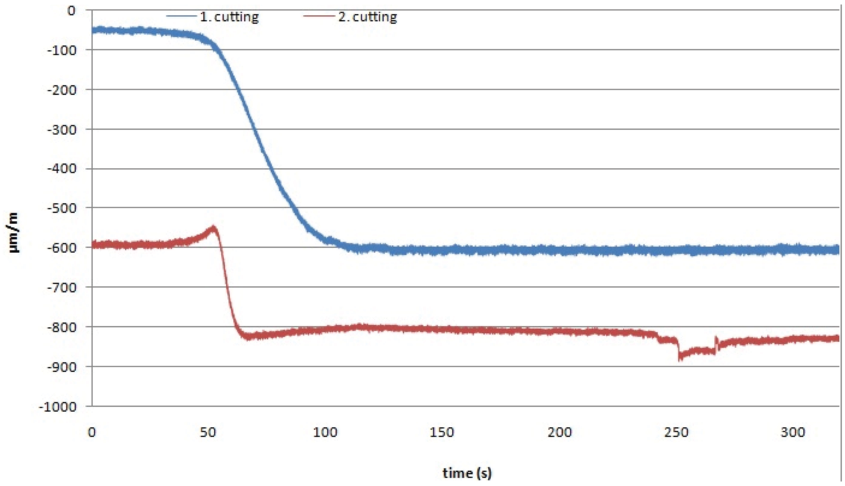


Fig. 7 Sample 2 (µm /m) / time(s)

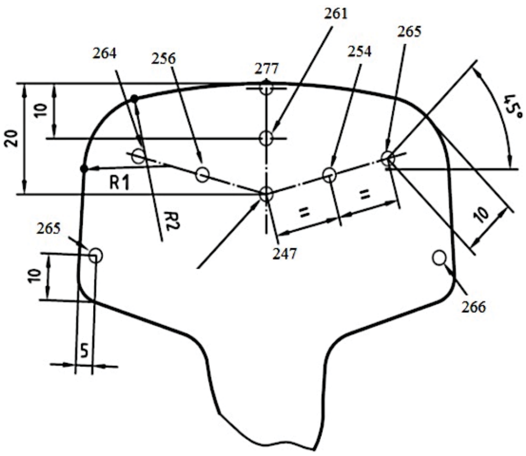


Fig. 8 Hardness measurements points

III. Results and Discussion

A. Residual Stress

Residual stress and strain values are given in Table II. In Fig. 7, blue line shows a first cutting and red line shows a second cutting for each sample. Two cutting processes were applied to extract 20 mm slice from the base material. During cutting, strain values were obtained with the help of software program belonging to the data collector device. First cutting was accepted reference and second cutting was important to determine the strain values. In red lines, obvious points were taken into account then strain data was found. After that, Hooke law was used to calculate residual stress:

$$\sigma = E * \varepsilon$$

Elastic Modulus was taken as 207000 MPa.

Results show that, all samples have tensile stress. While third rail has the highest residual stress and the value is 162.49 MPa, first sample has the lowest residual stress and that is 108.05 MPa.

TABLE III
Values of Residual Stress

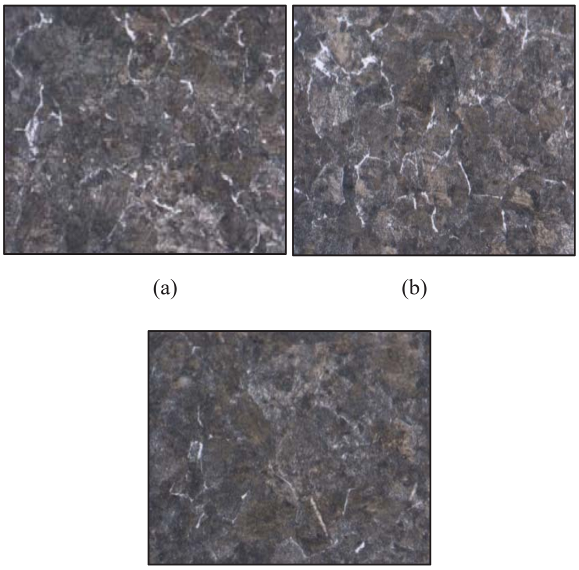
Sample (No)	Strain (µm)	Residual Stress (MPa)
1	522	108,05
2	710	146,97
3	785	162,49

B. Hardness

Hardness test was performed according to ASTM E647. Values of hardness are given in Fig. 8.

Hardness tests support the EN 13674-1 railway standard and the values are between 260 and 300 HBW. As expected, head parts of rails have higher hardness than center.

C. Microstructure Analysis



(a) (b)

(c)

Fig. 9 Microstructue of Rails (a) 1st Sample (b) 2nd Sample (c) 3rd Sample

LOM microstructure was taken same region (Rail Surface) for all rails. When Fig. 9 is examined, all samples have coarse pearlitic structure. However, third sample has fewer ferrite distribution than others. This sample also has highest residual stress.

D. XRD Analysis

TABLE IV
Phase Analysis by X-Ray Diffraction Method

Sample	44°	63°	83°
Sample 1	Ferrite, Fe_3C	Ferrite, Fe_3C	Ferrite, Fe_3C
Sample 2	Ferrite, Fe_3C	Ferrite, Fe_3C	Ferrite, Fe_3C
Sample 3	Ferrite, Fe_3C	Ferrite, Fe_3C	Ferrite, Fe_3C

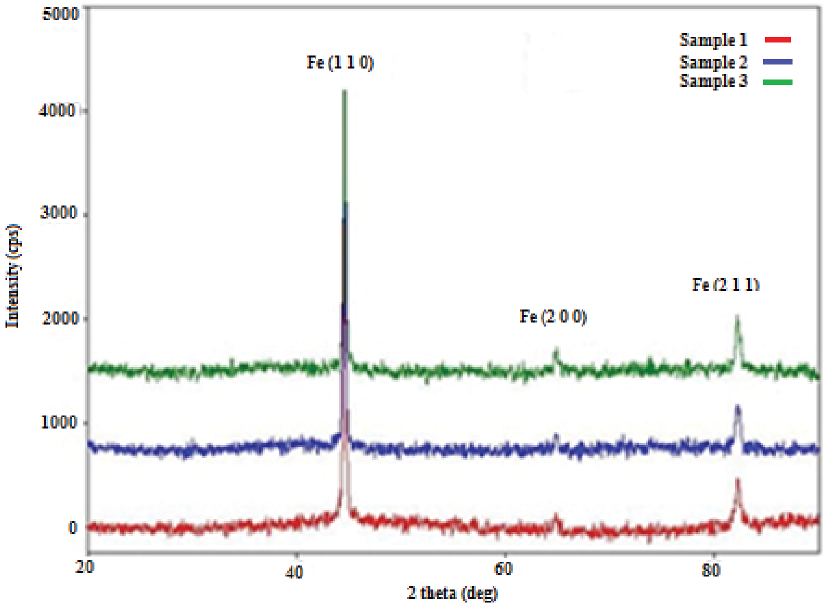


Fig. 10 XRD Measurements of samples

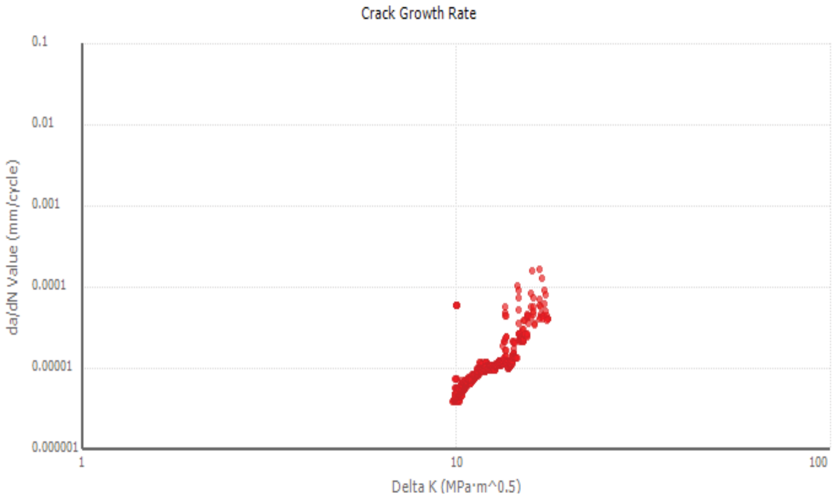


Fig. 11 Change of Fatigue crack growth rate (da/dN) versus Stress intensity factor (ΔK)

Crystalline of a compound was determined for each sample by X-ray diffraction. Values about phase analysis are given in Table IV.

Ferrite and Fe_3C phases were obtained at 2θ in 44°, 63° and 83° for all samples. Peaks belonging to the phases could be seen in (110), (200) and (211) planes. All rails have same phases at the same degrees but there is only difference about the intensity. Third sample has the highest intensity. This sample has also highest residual stress. So, it can be seen that residual stress cannot change types of phases but it can affect the intensity of phases.

E. Fatigue Crack Growth

The results belonging to all samples are presented in Fig. 11. The values of the samples provide the necessary conditions in the EN 13674-1 standard. The obtained values for 10 MPa√m and 13.5 MPa√m are shown in Table V.

TABLE V
RESULTS OF THE FATIGUE CRACK GROWTH RATE TESTS OF THE SAMPLES

Stress intensity Factor (ΔK)	**10 Mpa√m (mm/cycle)**	**13.5 Mpa√m (mm/cycle)**	**Residual Stress (MPa)**
Sample 1	1.48×10^{-5}	3.6×10^{-5}	108,05
Sample 2	1.50×10^{-5}	3.72×10^{-5}	146,97
Sample 3	1.61×10^{-5}	3.98×10^{-5}	162,49

As a result of fatigue crack growth test and residual stress measurement, there is a correlation between these two analyses. Fatigue crack growth rate was the highest in the 3rd Sample and also this rail has highest residual stress value. Tensile residual stress is dominant in specimens so it can affect mechanic properties of materials negatively. So that if the tensile residual stresses increase in materials, crack propagation resistance decreases. So fatigue crack growth rate increases.

IV. CONCLUSION

- All rails have between 260 and 300 hardness values
- Samples have coarse pearlitic structure when XRD and microstructure of samples is analyzed.
- Residual stress values show difference in all rails and values are under 250 MPa so they are accepted by standards.
- Residual stress change proportional with fatigue crack growth rate.

ACKNOWLEDGMENT

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