

Estimation of fatigue S-N curves for aluminium based on tensile strength – proposed method

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Abstract. The paper presents its own proposition of an analytical method for determining the S-N characteristic for aluminium material. The method is based on the value of the slope coefficient of the limited fatigue lifeline, determined based on the equation, which was proposed by analyzing a database of these parameters for a given group of materials. Also, the parameters of the method are tensile strength, yield strength, and the number of load cycles assigned to the knee point of the characteristic. A verification carrying out for three materials (AW-6063 T6, 2017-T4 & 2024 T351) shown that the proposed method gave better results than other methods presented in the literature.

1 Introduction

Production of aluminium in the world is growing every year. For example, in 2000 the production was 24 657 tonnes in the world, but in 2020 it was 65 269 tonnes [1], so it has raised about 165 %. Aluminium is using for building construction elements in cars, ships, spacecraft components, bicycle frames, trains, and aircraft. For this reason, it is important to know the strength of the material, which will be used. Most of the construction elements mentioned above have variable loading in time like the Hybrid Multimedia Mobile Stage presented in [2], tubular element presented in [3], or body structure of train [4]. So, it is important to know fatigue strength. To obtain fatigue characteristics of such material or component is costly, time-consuming, and requires specialist equipment and staff. Additionally, it is important to predict the fatigue life of the designed structure, before making a fatigue test of the whole construction. The schematic concept of that approaches can be found in [5]. Such tests are required for boogie frame for train and presented in [6]. Because of that has been developed many analytical methods to estimate such characteristics based on tensile strength, like the FITNET method [7], Lee & Taylor method [8], Schijve method [9], or Strzelecki method [10]. Unfortunately, these methods are well verified only for steels, which can be found in [6],[11],[12]. Authors haven't found verification of analytical methods for aluminium material or components. To fit that gap of knowledge has been verified methods mentioned above and proposed own.

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2 Proposed method

All verified analytical methods have described limited region of the S - N curve by Basquin equation as follow:

$$\log(N) = m_w \cdot \log(S_a) + b \tag{1}$$

where N is the number of cycles, m_w is the slope coefficient of the regression line, b is constant in the regression line and S_a is stress amplitude in MPa.

The proposed method and FITNET method have a second line of the S-N curve in the giga-cycle region, which contain a number of cycles from knee point N_k ($2 \cdot 10^6$ – proposed method, $1 \cdot 10^6$ – FITNET method) to N_0 ($5 \cdot 10^8$ – proposed method, $1 \cdot 10^8$ – FITNET method) expressed by the following formula:

$$\log(N) = m_g \cdot \log(S_a) + b_g \tag{2}$$

where m_g is the slope coefficient of the regression line, b is constant in the regression line and S_a is stress amplitude in MPa.

The method in [10] was proposed for steel materials and verified in [13]. The scheme presented in Fig. 1 is an extended version of the original version. The knee point N_k has been established as $2 \cdot 10^6$, where the original was 10^6 , which has a good agreement for steels [14]. It has changed because aluminium has a value for that constant from $1 \cdot 10^6$ up to $5 \cdot 10^6$ cycles acc. [15] and was chosen value close to the middle point of this range. Additionally, it was added a line with slope coefficient m_g equal to 22 it was suggested in [15]. Equations for slope coefficient m_w is expressed as follow [10]:

$$m_w = \frac{\log\left(\frac{2 \cdot 10^6}{N_{Sy}}\right)}{\log\left(\frac{0.9 S_y}{S_{f6}}\right)} \tag{3}$$

$$N_{Sy} = 400 \left(\frac{S_y}{S_u}\right)^{-10} \tag{4}$$

where S_u is tensile strength, S_y is yield strength and S_{f6} is fatigue strength for $2 \cdot 10^6$ cycles. The equations (3) and (4) were proposed for steels by analyzing 52 materials [10]. But verification presented below shown that has good agreements with experimental data for aluminium materials.

Fatigue limit S_f for second knee point N_0 , which was proposed as $5 \cdot 10^8$, is estimating according to the following equation [16]:

$$[0.53 - 5.66 \cdot (10^{-4}) \cdot S_u] \cdot S_u \tag{5}$$

Equation (5) was proposed in [16], after analyzing data presented in [17] and shown in Fig. 2. In Fig. 2 were marked lines for the proposed relation ultimate strength S_u to fatigue limit S_f according to analytical methods. $0.3 \cdot S_u$ is proposed in the FITNET method. Schijve proposed $0.35 \cdot S_u$. However, Lee & Taylor proposed $0.4 \cdot S_u$ up to 336 MPa, then S_f is equal to 130 MPa. Equation (5) has similar values as proposed by Lee & Taylor, which can be seen in Fig. 2 where lines are close to each other.

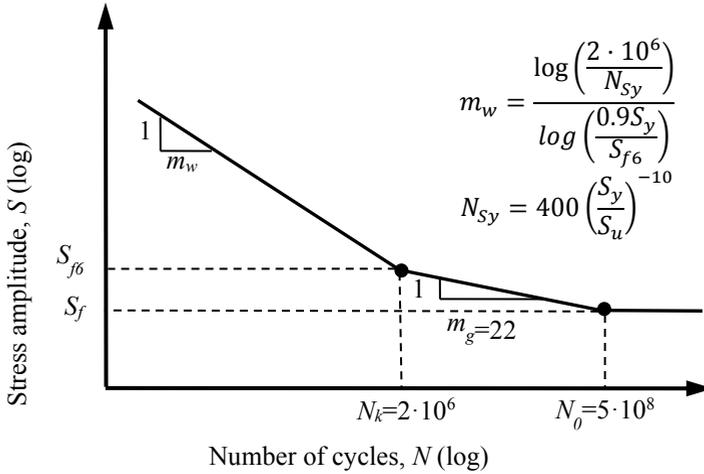


Fig.1. The proposed method for the estimation of the S-N curve for aluminium alloys in a limited life region.

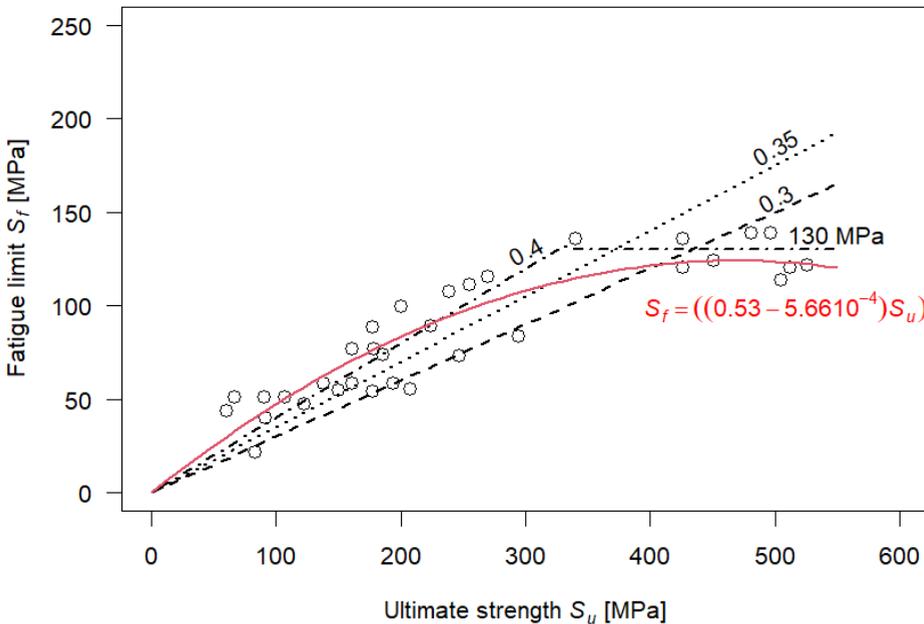


Fig.2. The fitting relations between tensile strength and rotating bending fatigue strength for aluminium alloys [17]

3 Experimental verification

Verification of the proposed method was made for 3 aluminium materials. The value of ultimate strength and yield strength for these materials was presented in Table 1. The first material AW-6063 T6 was loaded by rotary bending with a frequency of 50 Hz and the specimen diameter in the measuring point was 5 mm [18]. The second material 2017-T4 was loaded by machine for oscillatory bending with a frequency of 28.8 Hz and specimen

diameter in measuring point was 10 mm [19],[20]. The last material used for verification was 2024 T351 and tested by using ultrasonic fatigue testing equipment with the load train built into a servo-hydraulic test frame with frequency 20 kHz and specimen diameter in measuring point was 4 mm [21].

Table 1. Properties of tensile test for materials used for verification.

Material	S_u [MPa]	S_y [MPa]
AW-6063 T6 [18]	243	201
2017-T4 [19]	545	395
2024 T351 [21]	473	364

S-N curves for these materials were presented in Fig.3, Fig.4, and Fig.5. Additionally, it was marked S-N lines for FITNET, Lee & Taylor, Schijve, and the proposed method.

The estimated value of slope coefficient m_w , constant b , and standard deviation of the estimate error σ_s was presented in Table 2. The smallest standard deviation of the estimated error was bolded in Table 2.

The slope coefficients m_w for presented aluminium materials have lower value than the modal value for steel, which equals 10.9 and has been described in [22]. But estimated values by equation (3) have a close value to experiment for material 2017-T4 and 2024 T351 and the difference is only 0.2 and 0.1, respectively. For AW-6063 T6 obtained slope coefficient has over twice the larger value. This has occurred because the estimated fatigue limit S_{f6} is overestimated.

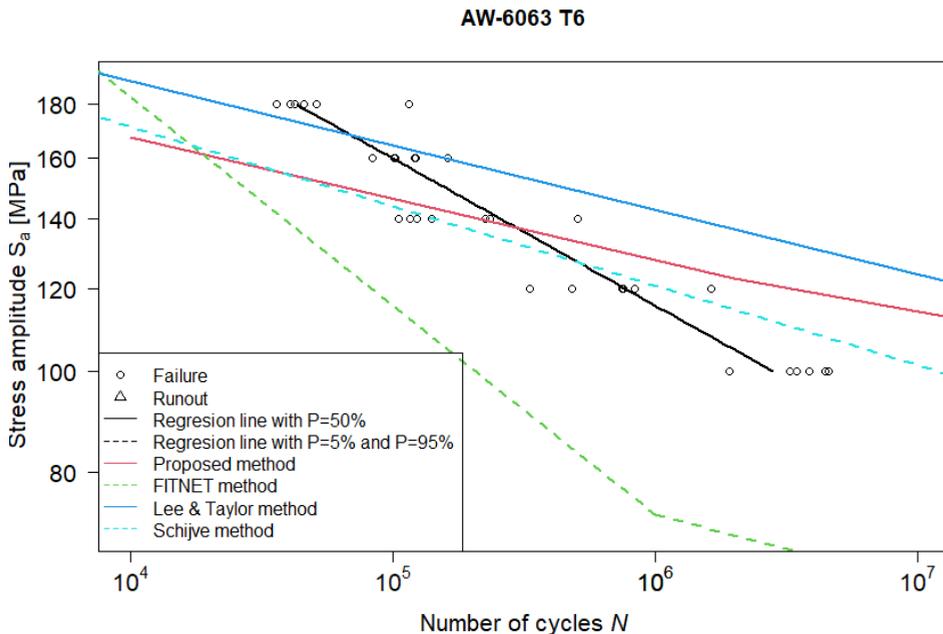


Fig.3. The S-N curve for AW-6063 T6 [18].

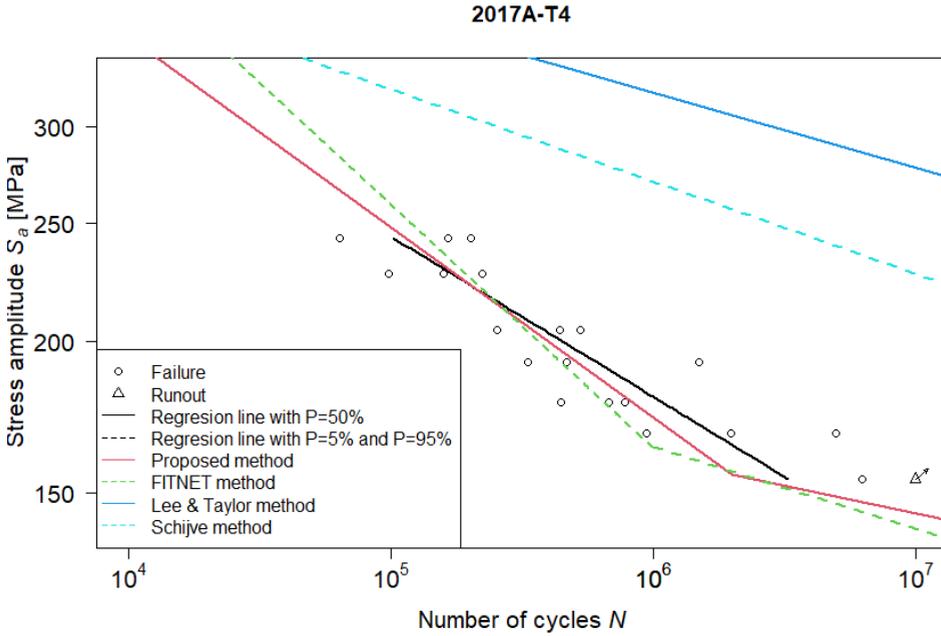


Fig.4. The S-N curve for 2017 T4 [19].

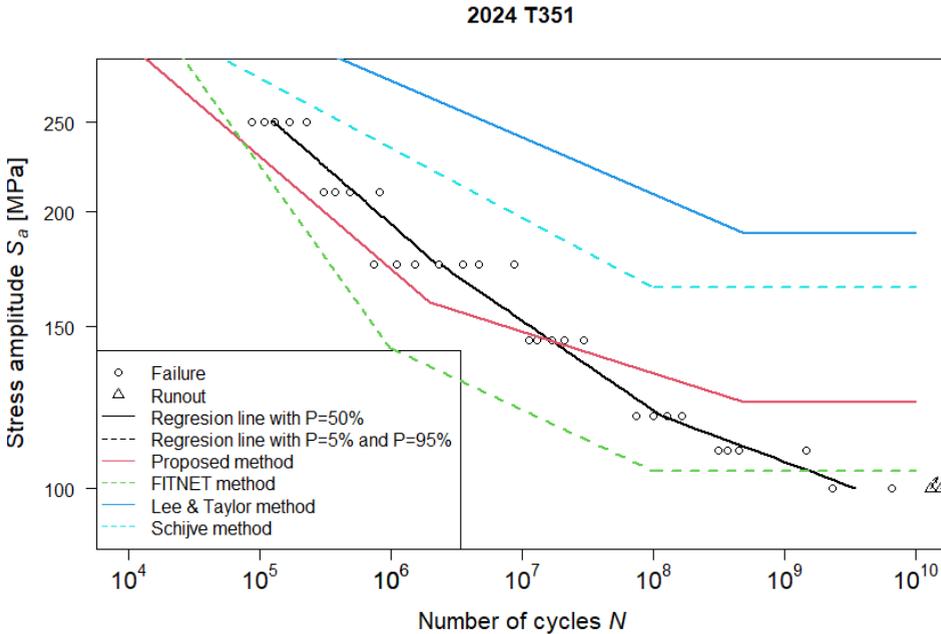


Fig.5. The S-N curve for 2024 T351 [21].

Only for 2024 T351 has been obtained fatigue life for over 10^7 cycles. In this case, the slope coefficient m_g has been obtained to 10.3. This value is lower than the 22 proposed in **Fig.1**. In the FITNET method m_g is proposed 15. However, the experimental value can be larger and obtain even 35 for example for AW 6082 [23]. So it should be vitrified in the context of recommendations in [15] and the FITNET method.

The standard deviation of the estimated error was calculated by the following equation:

$$\sigma_s = \sqrt{\frac{\sum_{i=1}^n (S_{a\text{ expri}} - S_{a\text{ call}})^2}{n-2}}, \tag{5}$$

where $S_{a\text{ expri}}$ is stress amplitude acc. experimental S-N curve, $S_{a\text{ expri}}$ is stress amplitude acc. S-N curve is estimated by analytical method and n is the number of specimens used. The smallest values of the standard deviation of the estimated error were bolded in Table 2. While the variation of the estimated error was calculated by the following equation:

$$V_e = \frac{\sigma_s}{S_a} \cdot 100\%, \tag{6}$$

where S_a is the mean value of all experimental stress amplitude.

Table 2. Results of calculation error of estimated fatigue curve.

Method	Material	Regression line		The standard deviation of the estimated error $\sigma_s = \sqrt{\frac{\sum_{i=1}^n (S_{a\text{ expri}} - S_{a\text{ call}})^2}{n-2}}$ [MPa]	Variance $V_e = \frac{\sigma_s}{S_a} \cdot 100\%$ [%]
		m_w	b		
Experiment	AW-6063 T6	-7.1	20.7	9.2	6.5
	2017-T4	-6.2	19.8	13.8	6.9
	2024 T351	-8.1	24.4	9.8	5.8
FITNET	AW-6063 T6	-5	15.3	60.7	43.4
	2017-T4	-5	17.1	37.6	18.9
	2024 T351	-5	16.8	38.4	23.1
Lee & Taylor	AW-6063 T6	-16.2	40.9	36.4	26.0
	2017-T4	-16.2	46.5	144.2	72.3
	2024 T351	-16.2	46.5	86.8	48.0
Schijve	AW-6063 T6	-13.2	33.4	34.3	24.5
	2017-T4	-13.2	38.0	93.3	46.8
	2024 T351	-13.2	37.2	43.5	24.0
Proposed method	AW-6063 T6	-17.0	44.1	17.8	12.7
	2017-T4	-6.4	22.6	15.5	7.8
	2024 T351	-8.2	24.6	19.9	12.0

The largest standard deviation of the estimated error was obtained by Lee & Taylor for all presented materials. The lowest value of σ_s has been got by the proposed method. For material 2017-T4 obtained error was close to the experimental value.

4 Discussion and conclusion

The constant slope coefficient m_w proposed in the FITNET method is not adequate for verified materials. It is constant, but m_w is changed for different materials. It was analyzed in [22] and concluded that the value of slope coefficient m_w proposed by FITNET (equal 5) has good agreement with elements with a sharp notch. In Lee & Taylor method and Schijve, there is a similar situation. Using equation (3) given better results. It can be seen that m_w is close to the experimental value for 2017-T4 and 2024 T351. Unfortunately, m_w for material AW-6063 T6 has a bigger difference between the experiment and the proposed method. This has occurred because when ultimate strength S_u has a lower value it is bigger dispersion in relation to fatigue limit S_f , see Fig.2.

It should be mentioned that the S-N curves estimated by Lee & Taylor method and Schijve method were overestimated fatigue strength for 2017-T4 and 2024 T351. For the third material AW-6063 T6 curves estimated by these methods were crossing experimental characteristics, so fatigue strength is firstly underestimated than overestimated. For that reason, these methods are not recommended for using by engineers to estimate the S-N curve for aluminium.

A better situation was with the S-N curve estimated by the FITNET method was underestimated for materials AW-6063 T6 and 2024 T351. The estimated curve by this method for material 2017-T4 was crossing experimental characteristic. For this reason, the FITNET method can be recommended to be used by engineers, but construction can be oversized. Additionally, the standard deviation of the estimated error for the FITNET method was twice larger than obtained the proposed method. Unfortunately, the proposed method overestimated fatigue strength for fatigue life larger than 10^6 cycles for AW-6063 T6 and over 10^8 cycles for 2024 T351. As it was mentioned above in the first paragraph, estimation of fatigue limit is troublesome for the low ultimate strength of aluminium and should be given an examination to find different relation.

The proposed method required verification for other aluminium materials and components. It is worthy addition to verify this method for torsion loading, which often occurs in construction elements. Additionally, it worth doing such analysis for materials different from steel and aluminium.

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