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ANALYSIS OF ACCELERATED METHODS FOR DETERMINATION OF FATIGUE CURVES

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Abstract

Specification of a full fatigue characteristic for a material and its structure elements takes a very long time and generates significant costs. There are many methods for accelerated obtainment of fatigue characteristics. In this work, a comparative analysis of selected methods of fatigue life specification for 12 kinds of materials has been made, on the basis of literature study. In the conclusions, distinctive features of results obtained by using these methods have been pointed out.

Keywords: *fatigue of materials, fatigue curves, accelerated methods*

1. Introduction

A material fatigue behavior for a high cycle range is usually described by a fatigue curve combining the number of cycles and stresses, that is, Wohler's diagram. The curve, also called S-N curve, is obtained by bringing a certain number of samples to destruction in result of sinusoidal action of load with different values. Standard [1] recommends that the number of samples examined at a given level of stress cannot be smaller than 3 and the number of levels should not be smaller than 5. The norm also says that the frequency of load changes should be contained in interval from 5 to 100Hz.

Such a way of Wöhler diagram obtainment is time consuming and generates high costs. For this reason, different methods for accelerated determination of fatigue curves have been developed and described in literature.

The purpose of this paper is a comparative analysis of these methods.

2. Description of selected methods for accelerated determination of fatigue curves

Below, there have been described selected methods for accelerated determination of Wöhler diagrams for the high cycle range.

The first of the discussed methods was discussed in work [2]. It assumes the Wöhler curve model as a straight line in a binary logarithmic scale whose beginning is in the point corresponding to monotonic tensile strength, denoted by the authors as S_u , with the number of N cycles equal to 1. For metals, the line end goes through the point corresponding to fatigue limit S_f with the number of N cycles equal to 1 which amounts from 10^6 or 10^7 to $5 \cdot 10^8$. This number depends on the material type, its microstructure and its machining method. For so defined beginning and end of the curve, it can be described by Basquin equation in the form:

$$S_a \ lub \ S_{Nf} = A(N)^b, \tag{1}$$

where S_a is fatigue amplitude of the cycle whose stress ratio R assumes random values, S_{Nf} is fatigue life, that is, stress amplitude for an oscillatory a cycle, such one for which $R = -1$, A is a coefficient whose value can be equal to S_u, real tensile strength σ_f or can be determined by means of real data regression. The curve slope is denoted by b letter.

For the purpose of further acceleration of S-N diagram obtainment process, the studied model assumes that the fatigue limit S_f for polished samples made of steel, can be estimated in the following way:

$$S_f \approx 0{,}5S_u \qquad je\dot{z}eli \ S_u \ \leq 1400 \ MPa \ , \tag{2}$$

$$S_f \approx 700 \ MPa \qquad je\dot{z}eli \ S_u \ \geq 1400 \ MPa. \tag{3}$$

For aluminum alloys S_f can be determined using dependence:

$$S_f \approx 0{,}35S_u \tag{4}$$

Next, coefficient b is calculated from the formula:

$$b = \frac{1}{6} log\left(\frac{S_f}{S_u}\right), \tag{5}$$

This method can be additionally modified with assessment of monotonic tensile strength S_u, on the basis of hardness according to Brinell scale [3], [2]. Steel with low and medium strength is estimated using the following formula:

$$S_u \approx 3{,}45HB. \tag{6}$$

Tensile strength for cast iron can be determined in a similar way:

$$S_u \approx 1{,}58HB - 86. \tag{7}$$

The other analyzed method has been presented in work [3]. It assumes that high cycle fatigue covers interval from 10^3 to 10^6 cycles. According to this method, Wöhler diagram for a high cycle area is created by connecting with a straight line a point corresponding to fatigue life S_{1000} for 10^3 cycles with point S_e being the fatigue limit for 10^6, $5\cdot10^7$ or $5\cdot10^8$. The value of fatigue strength can be estimated on the basis of formulas in table 1.

Tab. 1. Formulas for determination of fatigue life S1000

Type of material	Type of load	S_{1000}
All types	Bendindg	$0{,}9 \cdot S_u$
All types	Axial	$0{,}75 \cdot S_u$
Steels	Torsion	$0{,}72 \cdot S_u$
Non iron	Torsion	$0{,}63 \cdot S_u$
Żeliwo	Torsion	$1{,}17 \cdot S_u$

The authors also recommend to take into consideration reliability level $S_{1000,R}$ while determining S_{1000}:

$$S_{1000,R} = S_{1000} \cdot C_R, \tag{8}$$

The values of C_R coefficient have been presented in table 2.

Tab. 2. Values of C_R coefficient

Reliability level	C_R
0,5	1
0,9	0,897
0,95	0,868
0,99	0,814
0,999	0,753
0,9999	0,702
0,99999	0,659
0,999999	0,62

The value of fatigue limit S_e is determined according to a scheme expressed by the following formula:

$$S_e = S_{be} \cdot C_L \cdot C_S \cdot C_D \cdot C_R, \tag{9}$$

First of all, fatigue limit for bending S_{be} is calculated according to formulas which have been presented in table 3.

The next step is to determine amplitudes of stress S_f, on the basis of the number of cycles, using formula:

$$\frac{\log(10^3)-\log(10^6)}{\log(S_{1000})-\log(S_e)}=\frac{\log(10^3)-\log(N)}{\log(S_{1000})-\log(S_f)}, \tag{10}$$

Calculation of S_f from the formula is relatively complicated and inconvenient. However, it can be transformed into Basquin equation, determining b exponent and B coefficient on the basis of formulas:

$$b=-\frac{1}{3}\log\left(\frac{S_{1000}}{S_e}\right), \tag{11}$$

$$B=\frac{S_{1000}{}^2}{S_e}, \tag{12}$$

Tab. 3. Formulas for determination of fatigue limit S_{be} for bending

Type and microstructure of material	S_{be}	Cycles	Comments
Steel - ferrite	$0{,}58\cdot S_u$	10^6	-
Steel – ferrite + pearlite	$0{,}38\cdot S_u$	10^6	-
Stal – pearlite Stal – untempered martenzite	$0{,}38\cdot S_u$ $0{,}26\cdot S_u$	10^6 10^6	- -
Stal – highly tempered martenzite Stal – highly tempered martenzite + tempered bainite	$0{,}55\cdot S_u$ $0{,}5\cdot S_u$	10^6 10^6	- -
Stal – tempered bainite Stal – austenite Wrought Steels Wrought Steels Cast iron Aluminum alloys Aluminum alloys Sand cast aluminum	$0{,}5\cdot S_u$ $0{,}37\cdot S_u$ $0{,}5\cdot S_u$ $700\ MPa$ $0{,}4\cdot S_u$ $0{,}4\cdot S_u$ $130\ MPa$ $55\ MPa$	10^6 10^6 10^6 10^6 $5\cdot 10^7$ $5\cdot 10^8$ $5\cdot 10^8$ $5\cdot 10^8$	- - $S_u < 1400\ MPa$ $S_u \geq 1400\ MPa$ - $S_u < 336\ MPa$ $S_u \geq 336\ MPa$ -

Next, values of coefficients are determined: C_L – type of load coefficient (tab. 4) C_S – coefficient of the surface finish (fig.1 and 2) C_D - coefficient of size (fig. 3). C_R is determined in the same way as for $S_{1000,R}$.

Tab. 4. Values of coefficient C_L

Type of load	C_L	Uwagi
Pure axial	0,9	
Axial (with slight bending)	0,7	
Bending	1	
Torsional	0,58	Steels
Torsional	0,8	Żeliwa

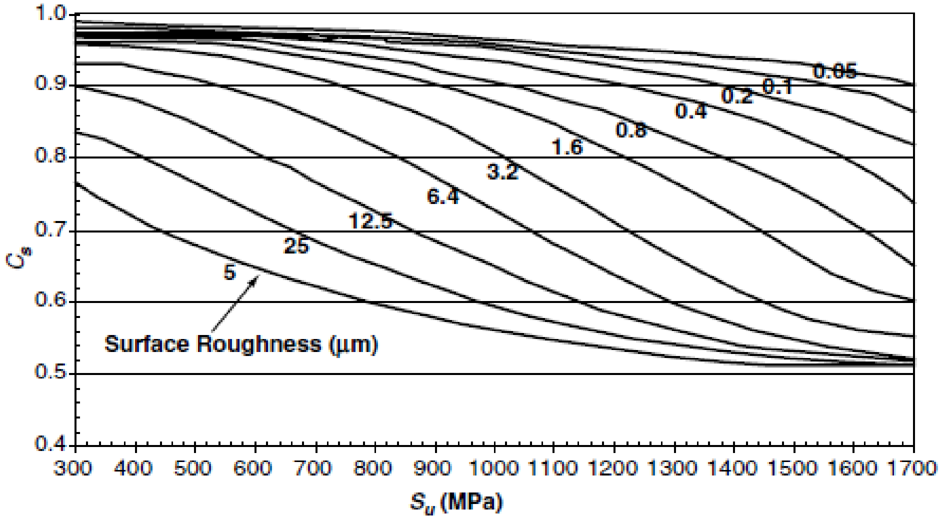

Fig. 1 – Chart for determination of C_S for known surface roughness (source – [3])

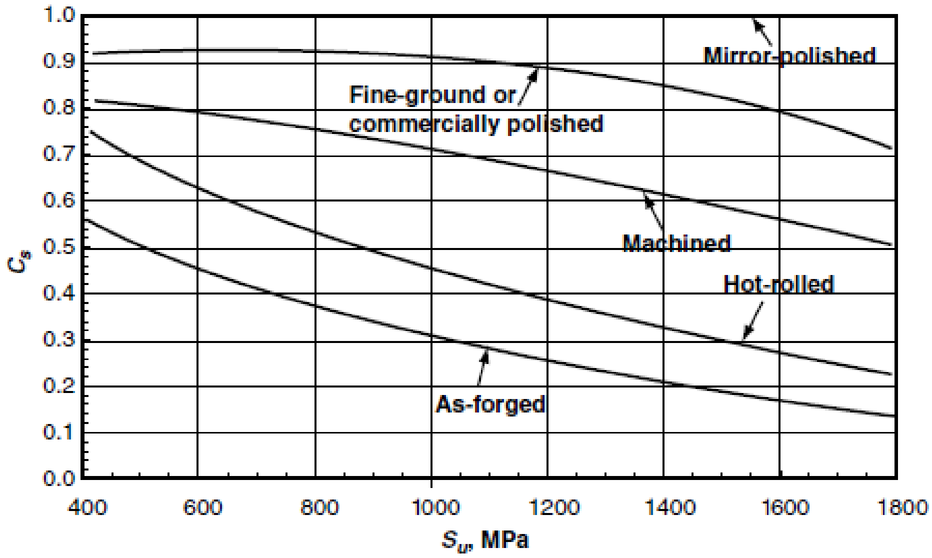

Fig. 2 – Chart for determination of C_S according to the machining type (source - [3])

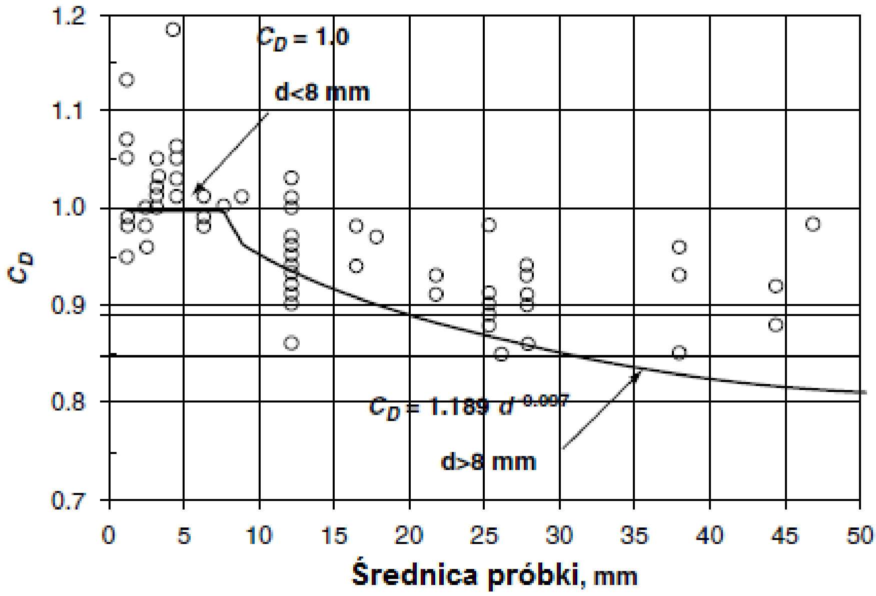

Fig. 3 – Chart for determination of CD (source – [3])

For so calculated quantities Basquin equation assumes the following form:

$$S_f = B(N)^b, \qquad (13)$$

The third analyzed method for accelerated determination of Wöhler curve is an approach described by FITNET procedures and work [4]. Fatigue diagram model described by FITNET procedures involves defining the angle of a straight line inclination and defining its end which is situated in the point corresponding to fatigue limit, denoted as Z_G.

The angle of a straight line inclination symbolized by coefficient m is determined from dependence presented in table 5.

Tab. 5. Values of m coefficient

Value of m coefficient	Type of specimen
16 ÷ 20	Surface hardened elements
8 ÷ 12	Fine Ground and polished elements
4 ÷ 10	Notched elements
3 ÷ 4	Welded elements

The value of fatigue limit is determined by multiplying tensile strength, denoted in FITNET procedures as R_m, through a proper coefficient selected from table 6.

Tab. 6. Coefficient for determination Z_G

Type of material	Values of Z_G for normal stressess	Values of Z_G for tangent stresses
Surface hardened steel	$0{,}4 \cdot R_m$	$0{,}577 \cdot R_m$
Stainless steel	$0{,}4 \cdot R_m$	$0{,}577 \cdot R_m$
Forged steel	$0{,}4 \cdot R_m$	$0{,}577 \cdot R_m$
Cast steel	$0{,}34 \cdot R_m$	$0{,}577 \cdot R_m$
Steels different from the above listed	$0{,}45 \cdot R_m$	$0{,}577 \cdot R_m$
Spheroidal cast iron	$0{,}34 \cdot R_m$	$0{,}65 \cdot R_m$
Ductile cast iron	$0{,}3 \cdot R_m$	$0{,}75 \cdot R_m$
Gray cast iron	$0{,}3 \cdot R_m$	$0{,}85 \cdot R_m$
Plastically worked aluminum alloys	$0{,}3 \cdot R_m$	$0{,}577 \cdot R_m$
Cast alluminum alloys	$0{,}3 \cdot R_m$	$0{,}75 \cdot R_m$

According to FITNET procedure, value N_G is 10^7 for steel and 10^8 for aluminum alloys. Coefficient of inclination of a straight line being a model of the fatigue curve is defined by formula:

$$ctg(\alpha) = m = \frac{\log \frac{N_G}{N}}{\log \frac{\sigma_a}{Z_G}}, \qquad (12)$$

where σ_a denotes permissible stress amplitude (fatigue life). Also, in case of this method, the above formulas can be transformed into the form of Basquin equation. Quantities b and B are determined in the following way:

$$b = -\frac{1}{m}, \tag{13}$$

$$B = Z_G N_g^{\frac{1}{m}}, \tag{14}$$

$$\sigma_a = B(N)^b. \tag{15}$$

For comparison, formulas and schematic diagrams, representing the above mentioned methods, were presented in figure 4.

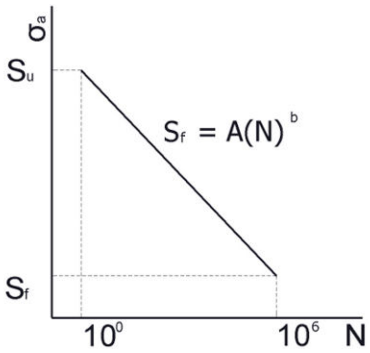

Fig. 4a. Scheme representing method S-N$_{Su}$

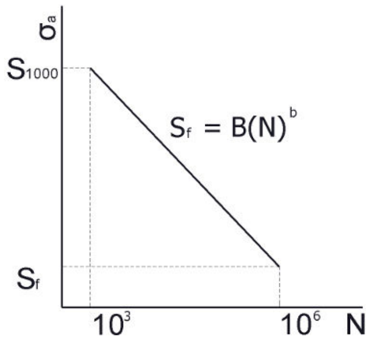

Fig. 4b. Scheme representing method FTaA

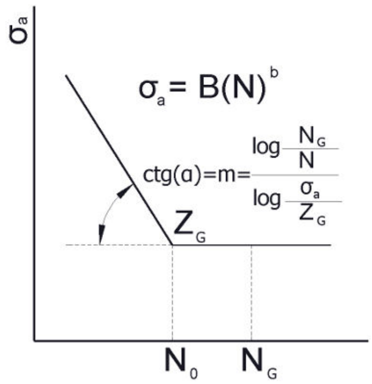

Fig. 4c. Scheme representing method FITNET

3. Verification of selected methods

Below, there have been presented results of verification of accelerated methods for determination of fatigue characteristics for a high cycle range. Abbreviations included in the legend denote: *„S-N$_{Su}$"* – method for determination of fatigue diagram, the basis of tensile strength described in [2]; *„S-N$_{HB}$"* – method for estimation of tensile strength on the basis of Brinell hardness, described in work [2]; *„FITNET"* – methods described in FITNET procedures; *„FTaA"* – method described in work [3]. These abbreviations are also used in the text for verification of the methods. Verification is carried out on the basis of the authors' own research.

Fig. 2 shows the result of verification for steel 10HNAP. For this material, characteristic most similar to the one obtained from experimental test is provided by "*FITNET*" method. However, it should be noted that the diagram obtained from this method runs above the real diagram throughout its whole length which means overestimation of fatigue life. The method which is based on tensile strength *„S-N$_{Su}$"*, yields a diagram which varies considerably from the real one in terms of direction coefficient, thereby, a part of the diagram runs below and a part above it.

„FTaA" method also yields a diagram which runs below the real one. However, attention is focused on the fact that they are parallel.

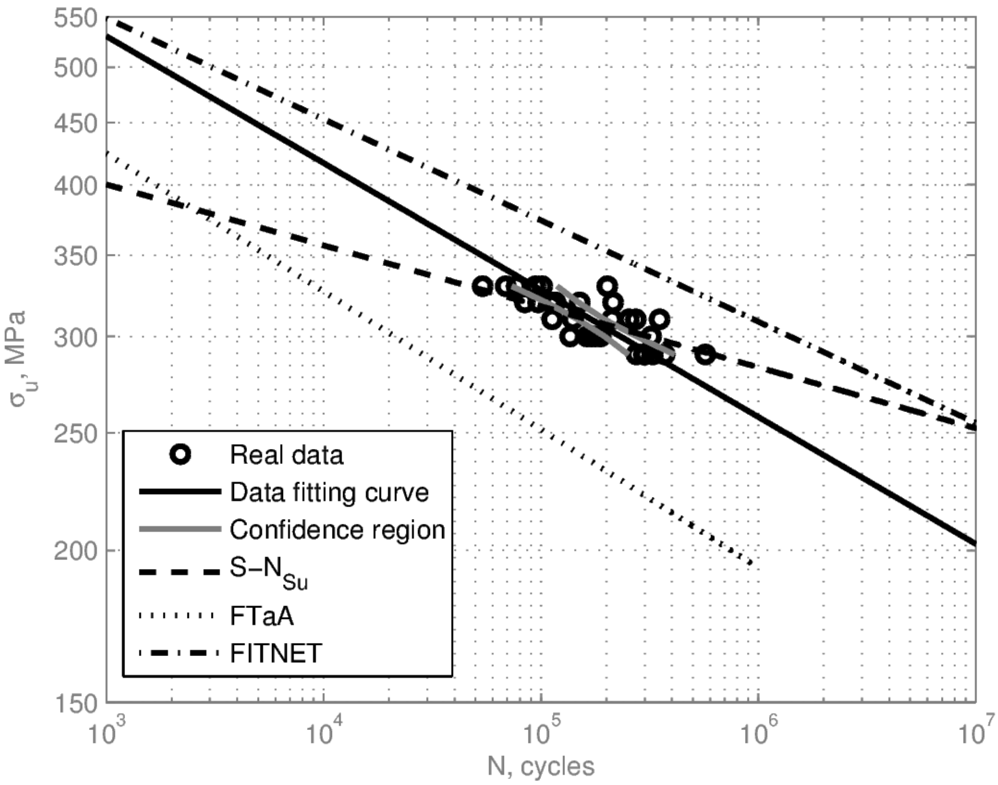

Fig. 5. Results of verification of method for accelerated determination of Wöhler diagram for steel 10HNAP

The next, presentation of diagrams (fig. 6) demonstrates the results for steel 30rNiMo8. In this case, a diagram, most similar to the real one, is provided by *„S-N_{Su}"* method. However, again the lines differ from each other in terms of direction. The diagram obtained with the use of *"FITNET"* method is situated significantly higher than the real one which means reassessment of fatigue life. The diagram obtained by *„FTaA"* method runs significantly lower than the real one and departs from it in respect of direction coefficient.

The next verified material is steel 40 CrMo4 (fig. 7). Also, for this steel, the diagram according to method *„S-N_{Su}"* is the most similar to the real one. However, it runs slightly above it throughout its whole length. .

Again, the diagram according to *"FITNET"* procedure is situated higher than the real one though is similar to it in terms of direction coefficient. *"FTaA"* method yields a diagram which runs significantly lower than the real one, and departs from it in terms of direction coefficient.

For BHW 25 steel (fig. 8), fatigue life characteristic from *"FITNET"* method is also situated higher than the real one throughout its whole length, and the two remaining ones, below. For this material, both the diagram from *"FITNET"* and from *"S-N_{Su}"* method differ from the real one in terms of direction coefficient. Diagram from *"FTaA"* method again differs significantly from the real one, both in terms of its position and direction.

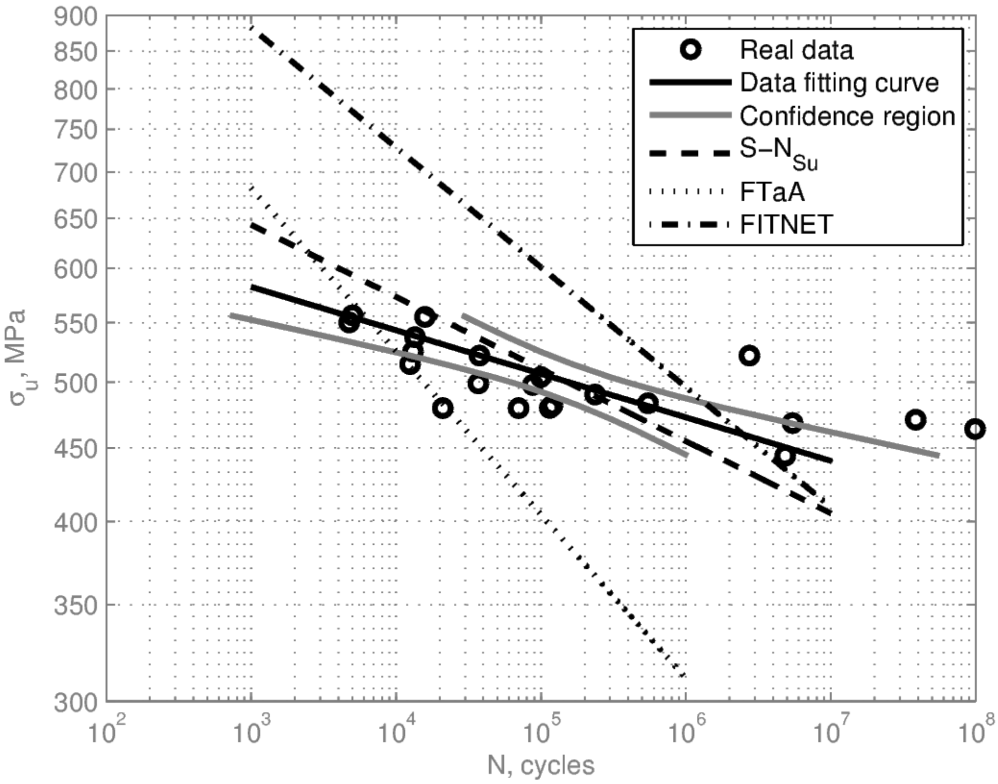

Fig. 6. Results of verification of method for accelerated determination of Wöhler diagram for steel 30CrNiMo8

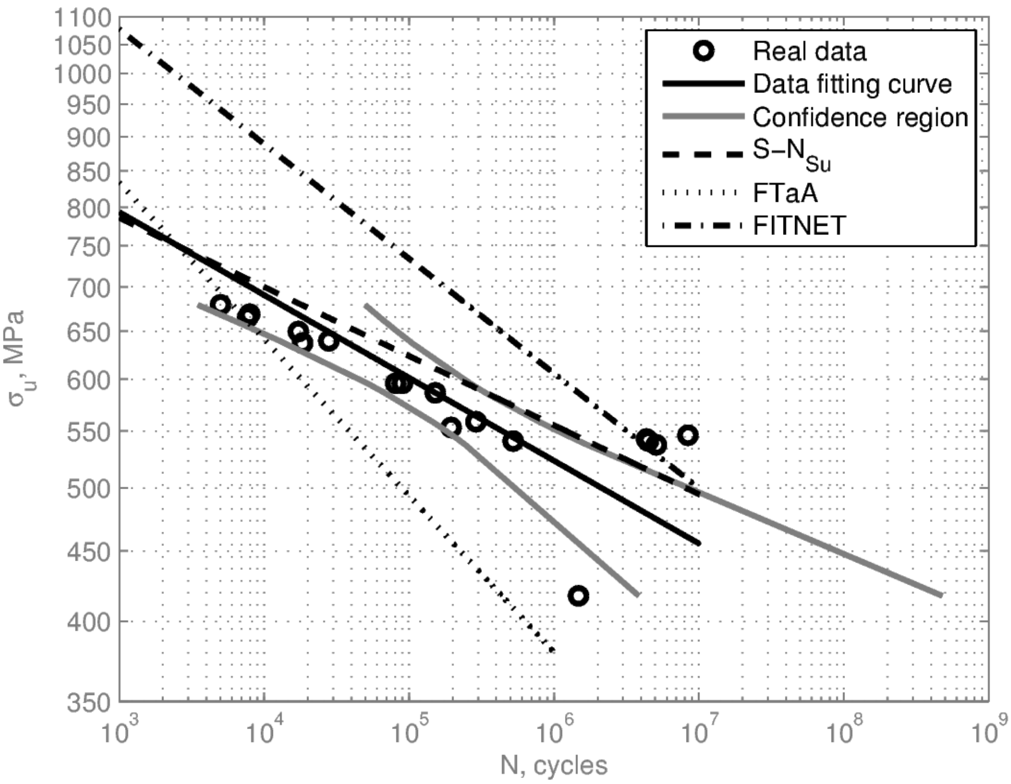

Fig. 7. Results of verification of method for accelerated determination of Wöhler diagram for steel 40 CrMo 4

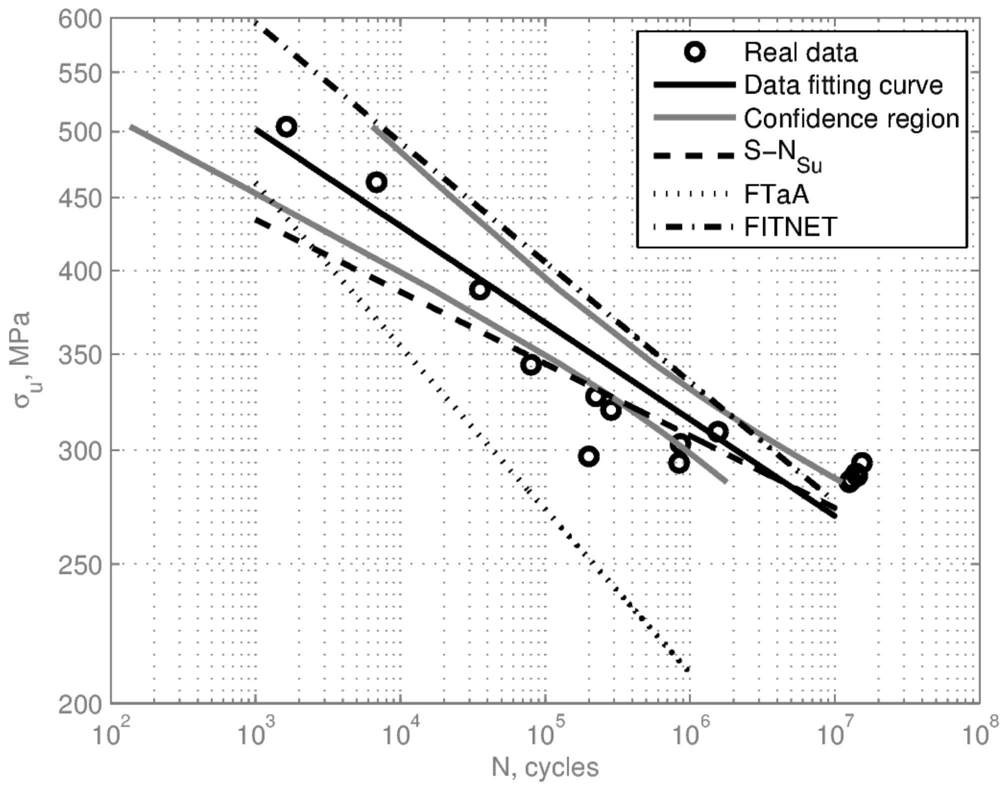

Fig. 8. Results of verification of method for accelerated determination of Wöhler diagram for steel BHW 25

The tendency for reassessment of *"FITNET"* procedure fatigue life is observed for steel Ck45 (fig. 9). Fatigue characteristic obtained using it is situated significantly higher than the real one. It is also different from it in terms of direction coefficient. For this material, the most similar in terms of direction and fatigue value appeared to be the characteristic obtained on the basis of "S-N_{Su}" method. The diagram obtained on the basis of Brinell toughness is also parallel to the real one but it runs significantly higher than it. Characteristic obtained on the basis of *"FTaA"* method departs from the real one in terms of direction and fatigue life value.

The following material for which methods for accelerated determination of Wöhler diagram have been verified is steel HSB 55 (fig. 10). For this material, the fatigue curve obtained from *"FITNET"* procedure is the most convergent with the real one in terms of the fatigue life value. However, again, for this material both these diagrams differ in terms of direction coefficient, thereby, the diagram from "*FITNET*" method lies in a hazardous area throughout up to $5 \cdot 10^4$ of fatigue life. Characteristic developed on the basis of *"S-N_{Su}"* method lies significantly lower than the real one, however, is consistent with it in terms of direction coefficient. *"FTaA"* method yields Wholer diagram which is most different from the real one.

Fig. 11 presents calculation results for another material, steel SPV 50. Like previously, the diagram from *"FITNET"* method is different from the real one in terms of direction coefficient, thereby, it lies in the area of hazard through up to $2 \cdot 10^5$ cycles. Methods *„S-N_{Su}"* and *„S-N_{HB}"* yield diagrams consistent with the real one, though, more inclined. The diagram according to *"FTaA"* approach differs most from the real one, in this case as well.

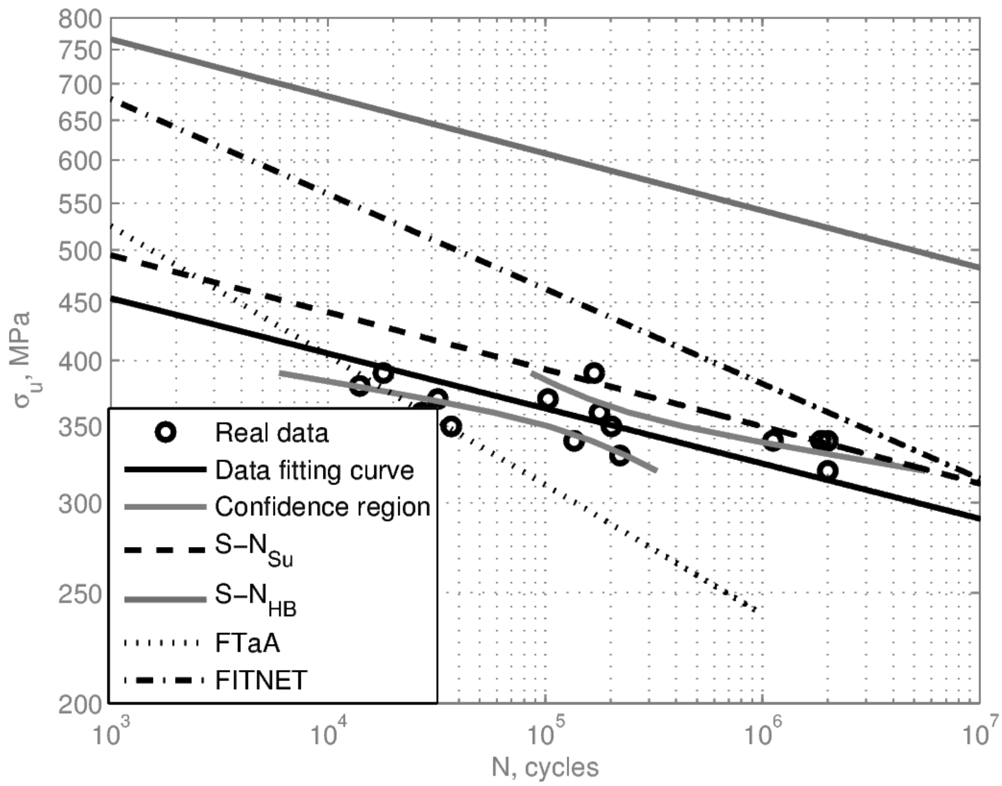

Fig. 9. Results of verification of method for accelerated determination of Wöhler diagram for steel Ck45

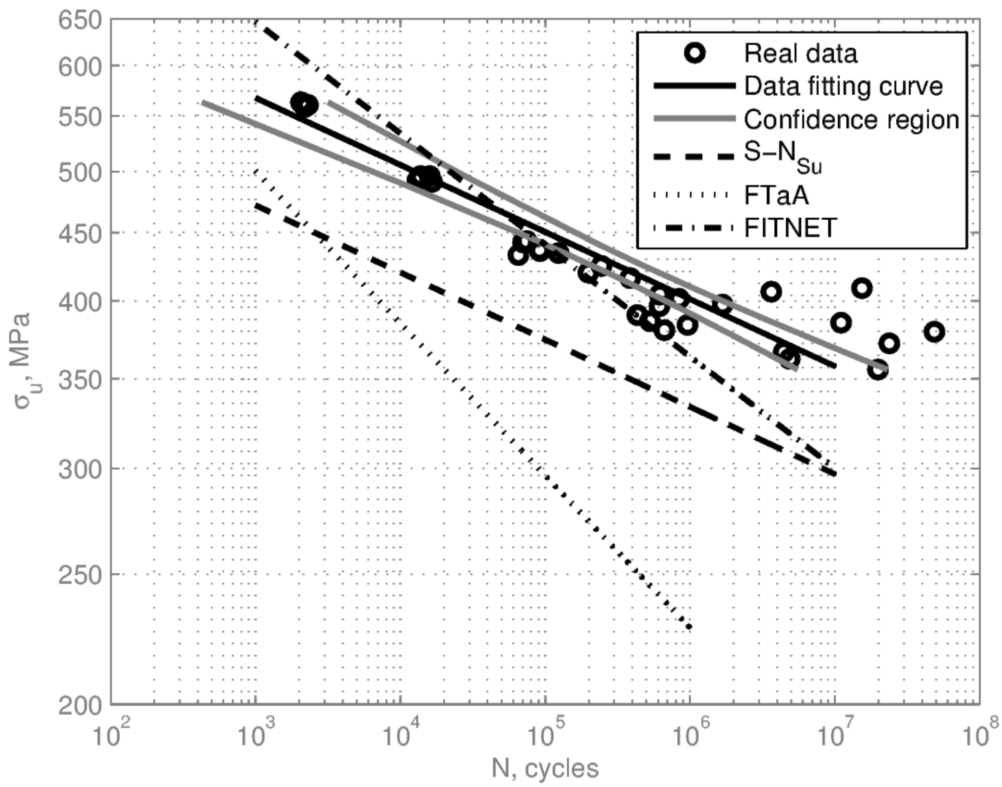

Fig. 10. Results of verification of method for accelerated determination of Wöhler diagram for steel HSB55

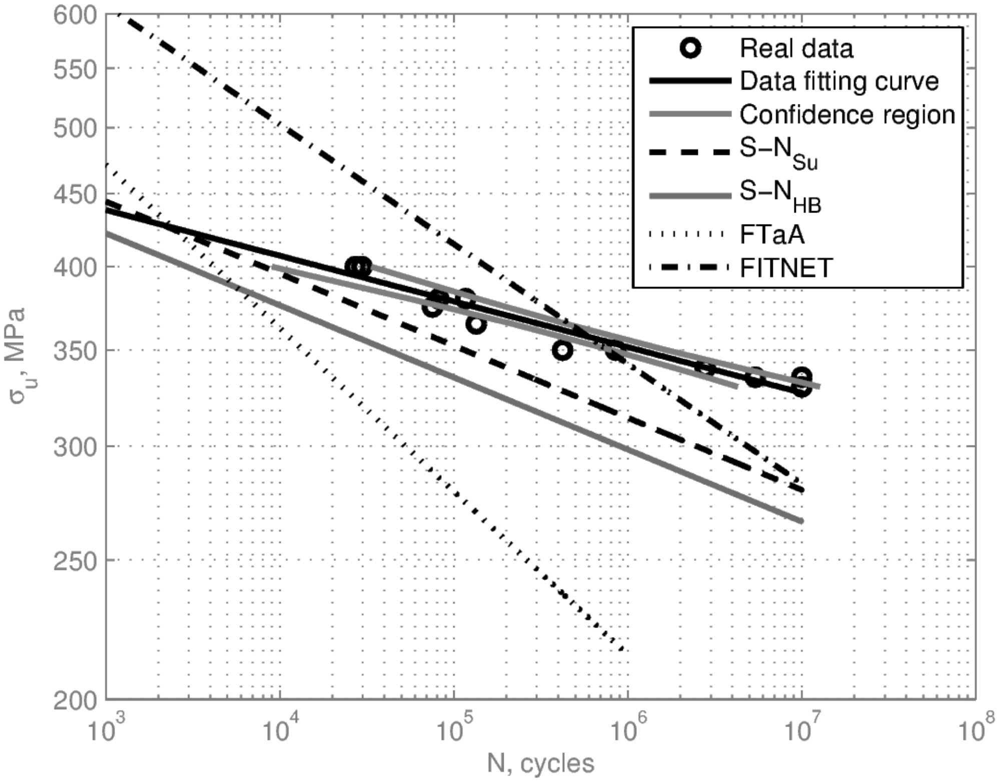

Fig. 11. Results of verification of method for accelerated determination of Wöhler diagram for steel SPV 50

The diagram created for steel St52 on the basis of *"FITNET"* procedure is very similar to the real data diagram in terms of direction coefficient, however, also for this material it is reassessed (fig. 12.). *"S-N_{Su}"* approach provides a diagram which is more consistent with the real one in terms of fatigue life but different from it in terms of direction coefficient. *"FTaA"* method yields a diagram mostly consistent with the real one but lying significantly lower than values obtained from tests.

Comparison of methods was also made for steel St37 (fig. 13). Besides, Wöhler diagram obtained from *"FITNET"* procedure is consistent with the real one in respect of direction coefficient, though it lies above it, in the area of hazard. The method using tensile strength *"S-N_{Su}"* provides a diagram situated similarly to the real one in terms of stress amplitude values, however, different from it in respect of direction. The diagram direction is more similar for *"FTaA"* method, though it lies below the real one.

In figure 14 there are diagrams obtained for steel StE 460. Again, the diagram created according to *"FITNET"* procedure lies above the material fatigue characteristic and it is most similar in terms of direction coefficient. Like for the previous material, the diagram created on the basis of tensile strength, *„S-N_{Su}"*, departs from the real one in respect of slope. This time almost throughout its length it lies above it. *"FTaA"* method provides a diagram situated closer to the real one differing, though, in terms of direction coefficient.

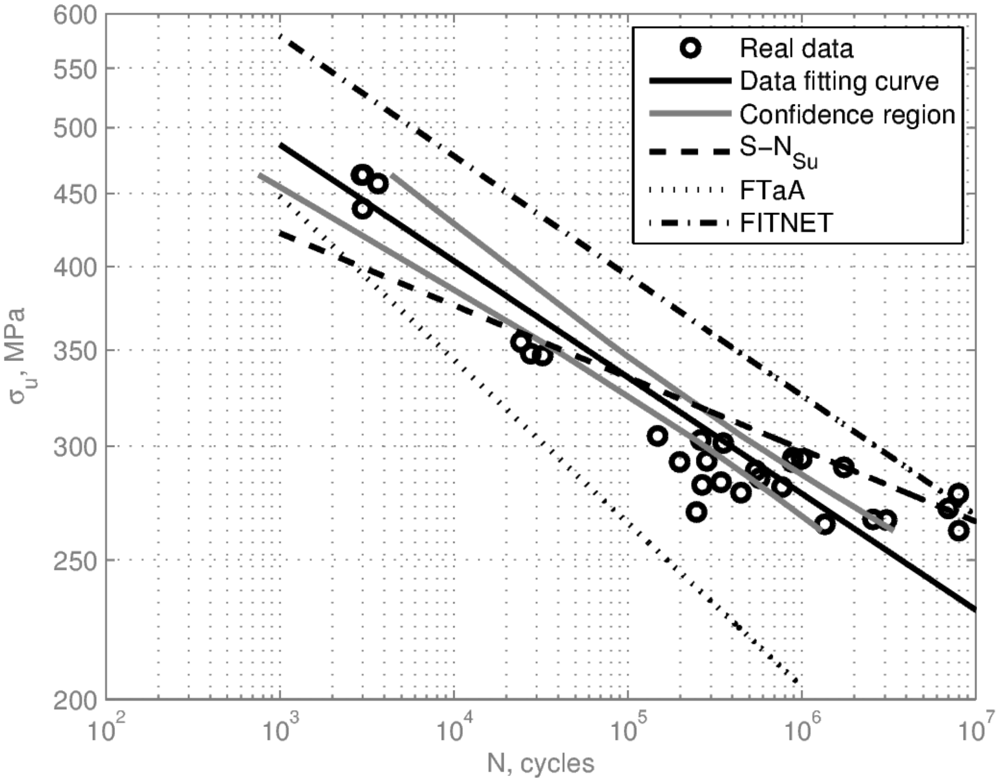

Fig. 12. Results of verification of method for accelerated determination of Wöhler diagram for steel St52

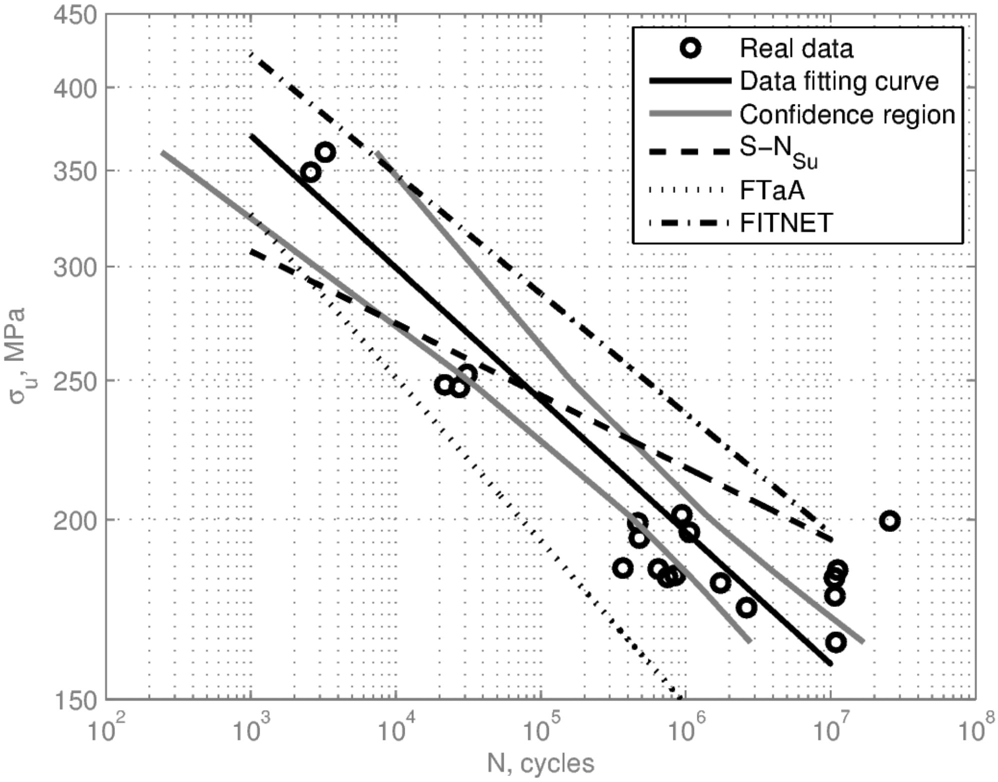

Fig. 13. Results of verification of method for accelerated determination of Wöhler diagram for steel St37

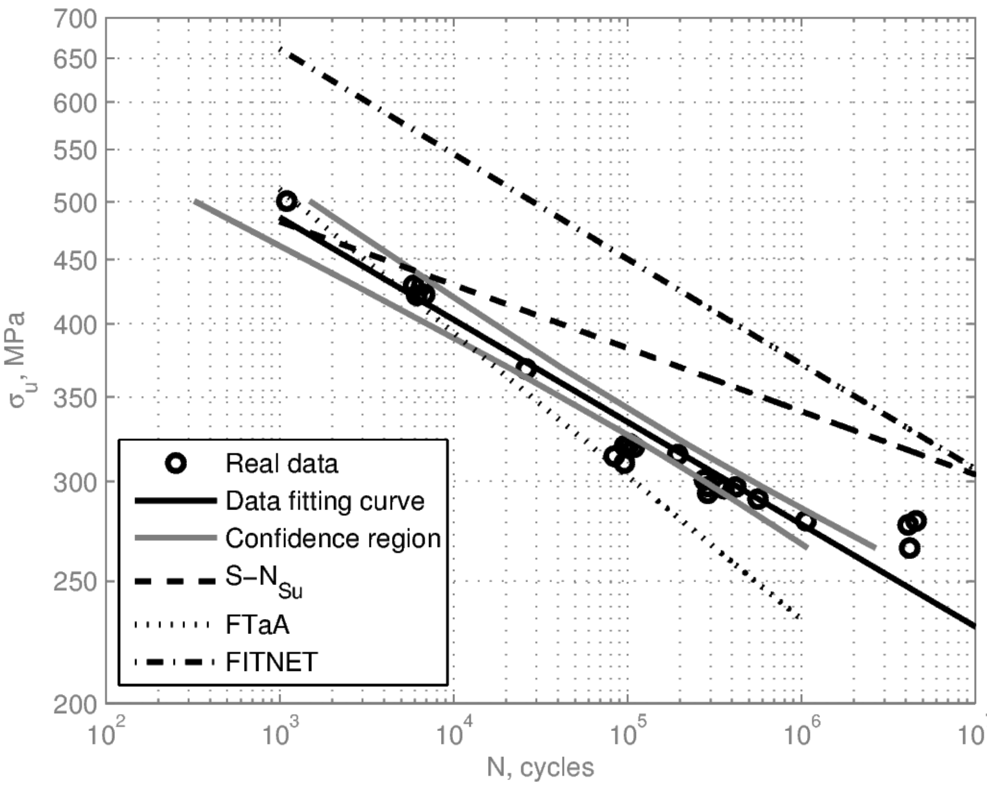

Fig. 14. Results of verification of method for accelerated determination of Wöhler diagram for steel StE 460

The next presentation of Wöhler diagrams (fig. 15) was made for steel StE 690. *„S-N_{Su}"* method yields a diagram lying closest to the real one and similar in terms of direction. Method from *"FITNET"* procedure again provides a diagram situated in the area of hazard. For StE 690 steel also departs from the real one in respect of direction coefficient. The diagram obtained from *"FTaA"* method lies below the real one, also for this material and differs from it in terms of direction.

The last material for which accelerated methods for Wöhler diagram determination have been compared is steel X5CrNi18 (fig.16). For this material the diagram obtained from *"FITNET"* procedure departs from the real one, thereby, up to 10 cycles lie above it, running below the real line . Also in this case, *„S-N_{Su}"* method appears to be an approach providing a diagram most similar to fatigue characteristic in terms of both direction and fatigue life. The diagram obtained on the basis of *"FTaA"* method is most divergent from the real one.

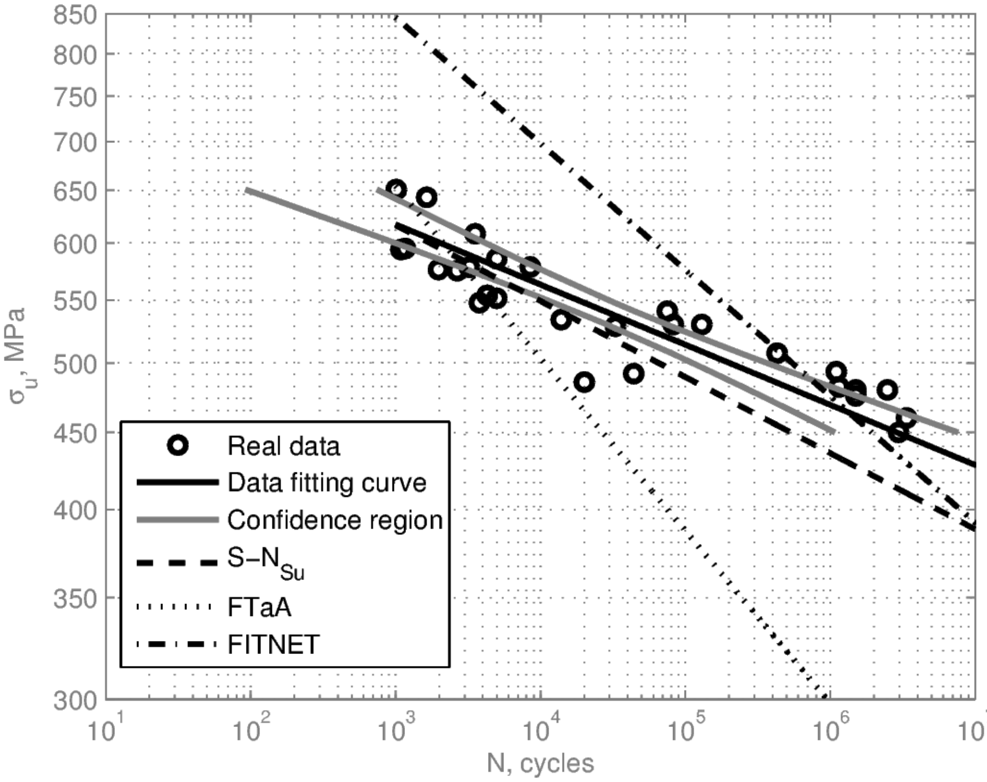

Fig. 15. Results of verification of method for accelerated determination of Wöhler diagram for steel StE 690

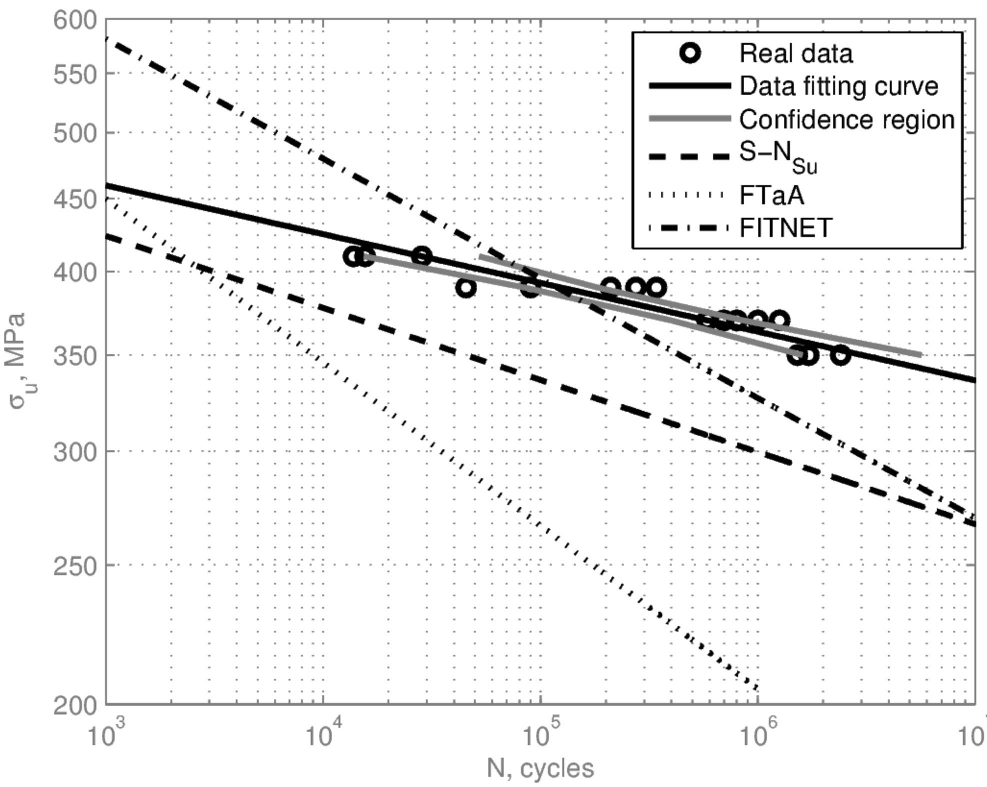

Fig. 16. Results of verification of method for accelerated determination of Wöhler diagram for steel X5CrNi18

4. Conclusions

Summing up, it can be said that Wöhler diagram which is most similar to the real one is obtained from methods "S-N_{Su}" and "S-N_{HB}" However, they usually differ in terms of direction coefficient. Most often it is situated, partly or entirely, below the real characteristic, that is, in the area of no hazard. The method described in "*FITNET*" procedure most frequently provides a diagram lying above the real one, that is, in the area hazardous due to reassessment of fatigue life. They also differ with direction coefficients. "*FTaA*" method using the diagram initial point as fatigue life for a thousand of cycles provides a diagram which is the least similar to the real one. Usually, they differ significantly in respect of direction coefficient, and the estimated diagram most frequently lies below the experimental one.

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