

Article

Fatigue Life for Different Stress Concentration Factors for Stainless Steel 1.4301

Przemysław Strzelecki ^{1,*} , Adam Mazurkiewicz ¹, Janusz Musiał ¹, Tomasz Tomaszewski ¹ and Małgorzata Słomion ²

¹ Mechanical Engineering Department, University of Science and Technology, Kaliskiego 7 Street, 85-789 Bydgoszcz, Poland; adam.mazurkiewicz@utp.edu.pl (A.M.); janusz.musial@utp.edu.pl (J.M.); tomasz.tomaszewski@utp.edu.pl (T.T.)

² Faculty of Management, University of Science and Technology, Kaliskiego 7 Street, 85-789 Bydgoszcz, Poland; malgorzata.slomion@utp.edu.pl

* Correspondence: p.strzelecki@utp.edu.pl; Tel.: +48-52-340-86-72

Received: 26 September 2019; Accepted: 5 November 2019; Published: 8 November 2019



Abstract: This paper presents the results of the static tensile and fatigue life tests under rotating bending of round 1.4301 (AISI 304) steel samples. The fatigue tests were carried out on smooth and notched samples with three different rounding angles with a shape factor of 1.4, 2 and 2.6. A fatigue life was determined for samples with different shape factors subject to identical loads. The results showed that the scatter of fatigue test results decreases with an increase in shape factor. To evaluate the cracking properties (cracking mode and mechanism), microstructure and fractographic tests of the fractured samples were carried out.

Keywords: fatigue design; S–N curve; high-cycle fatigue; stainless steel

1. Introduction

The use of stainless steel in engineering has grown significantly in recent years. In 2018, the use of stainless steel in the industry has grown over 60% compared to 2010 [1], estimated at 50.7 Mt [2]. Due to the common use of this material in engineering, tests to evaluate its structure and properties are crucial. As a result, several articles on its properties have been published [3–7]. Since the material is often used in mechanical engineering, evaluation of its basic mechanical properties, including tensile strength and fatigue life, is crucial.

To determine the fatigue life of a material, an S–N curve (stress vs. number of cycles) is often determined for the smooth samples and a stress concentration factor is calculated to correct the results for a specific structural component [8]. S–N curves can be determined by different models, the comparison of which is presented in [9–11]. The last square method is the most simple and commonly used method to estimate model parameters and it is presented in standard [12] and [13]. Other methods, such as the maximum likelihood method [14–16] and bootstrap method [17], are also used. Recently, a new method to calculate the fatigue strength for different geometries was presented by Ai et al. [9]. Some of the authors also conducted tests with stepwise increasing amplitude [18]. To increase the reliability of the estimated fatigue life, a reliability factor is also determined depending on the required probability of failure [8,12,19]. The procedure assumes a constant scatter of results for each geometry of the tested component; however, no such relation was shown by the researchers.

A study [20] (pp. 377–380) by Schijve presents the tests carried out on two structural components in which the fatigue life at 50% failure probability was 8.5 times higher for two different components. For the same components, at the failure probability of 1%, the difference in fatigue life was 2.3 times.

The study aimed to verify whether the scatter of fatigue test results varies depending on the stress concentration factor. The 1.4301 stainless steel samples, a material commonly used in mechanical engineering, were used as a test material. The test results showed that the scatter of fatigue life depends on the geometry of the components.

2. Materials and Methods

Austenitic 1.4301 (AISI 304) stainless steel was used in the tests [2]. The chemical composition of steel was measured by using a spectrometer, the Oxford Instrument Foundry-Master UV (Oxford Instrument, Abingdon, UK), which fulfils the standard requirements [21] and is shown in Table 1. The samples were made from a 10 mm drawn bar in a raw state, with the dimensions consistent with the standard requirements [22]. The drawing was made at room temperature. The smooth samples for fatigue tests were prepared in accordance with Figure 1a, and the notched samples were prepared in accordance with Figure 1b with the dimensions specified in Table 2.

Table 1. Chemical composition of austenitic steel 1.4301 (X5CrNi18-10) according to [21] and measured value.

Item	% by Mass						
	C	Si	Mn	P	S	Cr	Ni
Standard requirements [21]	≤0.07	≤1.00	≤2.00	≤0.045	≤0.015	17.5–19.5	8.0–10.5
Measured value	0.05	0.75	1.56	0.043	0.010	18.1	9.7

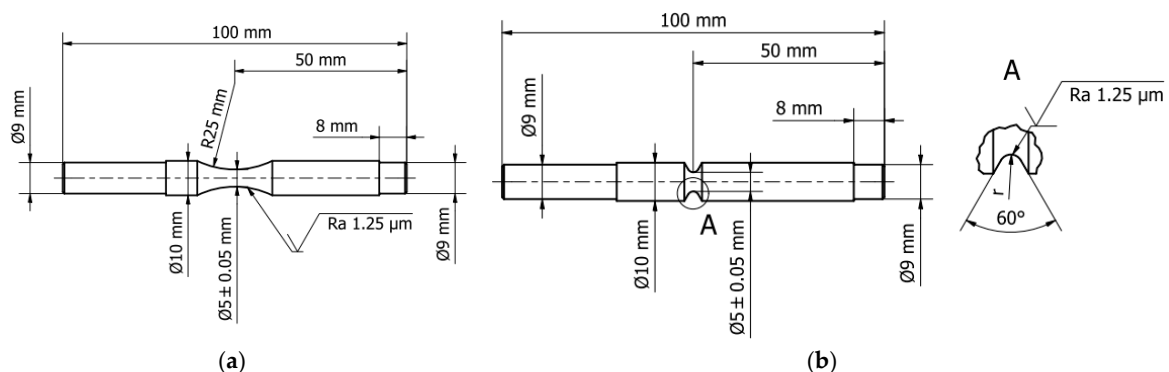


Figure 1. Geometry of the specimen for fatigue testing (a) Smooth; (b) Notched.

Table 2. Dimensions of the notched specimens.

No.	r [mm]	K_t [-]
1	1.5	1.4
2	0.5	2
3	0.25	2.6

A static tension test was carried out on an Instron 8874 testing machine in accordance with the standard requirements [23]. The strain rate was 0.0198 mm/s, which is similar to that presented in [24]. A rotating bending machine described in [25] was used in the fatigue tests. Figure 2 shows the test stand diagram. On one side, the sample was attached to the test stand shaft via a clamp and on the other side a bearing with a load m was mounted. The shaft speed M_0 was 3000 min⁻¹ at a loading frequency of 50 Hz. The bending moment M_g was equal to the load m suspended on the bearing multiplied by the distance between the bearing center and the point of minimum cross-section l , which was 46 mm. A load weighing between 5 kg and 13.8 kg was applied. A rotating bending test was carried out in accordance with the standard procedure [26]. The measuring accuracy was 1.15% with a permissible accuracy of 1.3% [26].

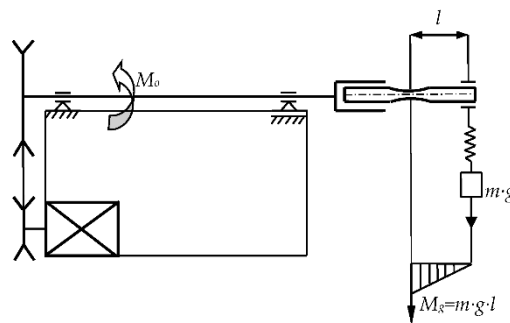


Figure 2. Scheme of test equipment for rotating bending.

3. Results

Table 3 shows the mechanical properties calculated based on an axial tensile test at a constant loading rate. The table shows the average values calculated for 20 tests. Figure 3 shows an example stress–strain diagram for the test. The values for yield strength and ultimate strength are higher than the minimum requirements in [27] which should be least 350 MPa and 700 MPa for S_y and S_u , respectively. It should be mentioned that the requirements for plate steel according to [28] are of a lower value, with a minimum of 230 MPa and 540 MPa for yield strength and ultimate strength, respectively. Mechanical properties are different for drawn and plane bars because a bar has high plastic strain after drawing.

Table 3. Mechanical properties for the 1.4301 steel.

E [MPa]	S_u [MPa]	S_y [MPa]	A [%]	Z [%]
206 553	803	561	78.3	43.8

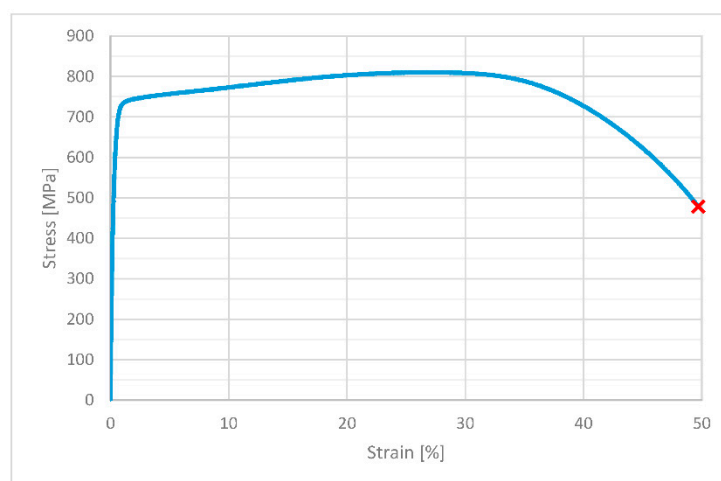


Figure 3. Stress–strain curve for static load for exemplary specimen.

The microstructure was tested in a cross section perpendicular to the axis of the sample without a load using a scanning digital microscope, the OLYMPUS LEXT OLS4100 Laser Confocal Microscope (Olympus, Tokyo, Japan). Figure 4 shows the example image. Austenite grains are dominant in the visible structure and have sizes between 20 μm and 50 μm . The mean size of the grains was 38.3 μm and the standard deviation was equal to 8.5 μm . The calculation was made by ImageJ software version 1.52a on four images, taken from the scanning digital microscope OLYMPUS LEXT OLS4100, according to standard [29]. A small number of martensite grains (approximate 6%) can also be observed.

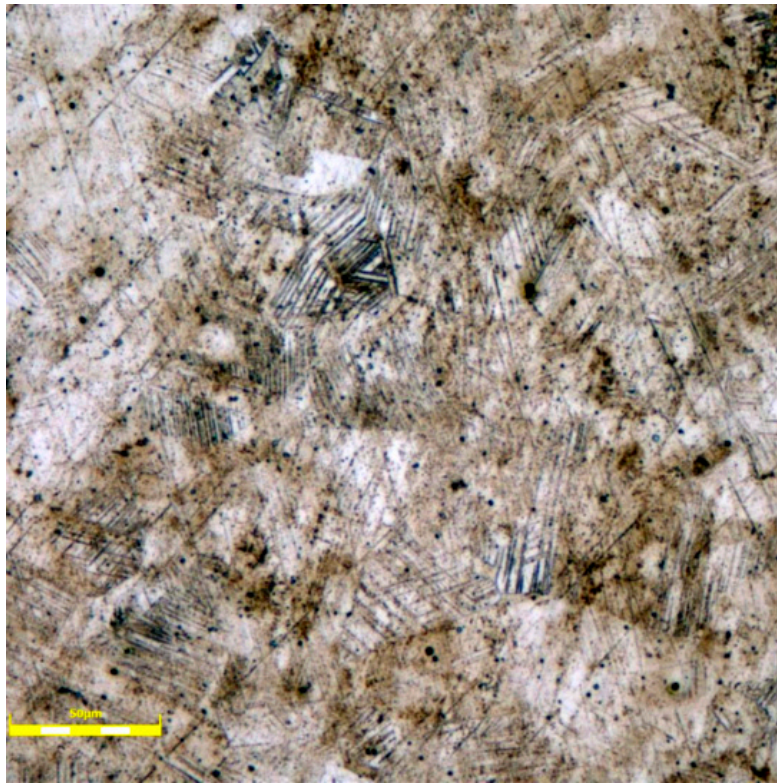


Figure 4. Microstructure of the 1.4301 stainless steel, transverse section in etched.

A fractography of fatigue fractures was carried out for each sample geometry. Figure 5 shows the example fracture images. The tests were carried out on a JEOL JSM-6610 Series Scanning Electron Microscope (JEOL, Tokyo, Japan). The study aimed to compare the propagation of the fatigue cracks for different sample geometries. Figure 5a shows the fracture of a smooth sample. It differs from the fractures in the notched samples, which are often used in fatigue tests. In smooth samples, the crack propagates from several points around the entire sample perimeter, as seen in Figure 5a. In notched samples, the crack is initiated in one or two points, as seen in Figure 5b–d. The results are consistent with the results presented in [30] (p. 39).

Figure 6 shows the relationship between fatigue lives and applied nominal stresses. The number of samples and the load range were determined in accordance with [13]. A minimum of 30 tests at five different load levels, i.e., six samples for a single load, were carried out for each sample geometry. The load levels were selected to obtain the fatigue life between 2×10^4 and 10^6 cycles.

A 3-parameter Weibull distribution [31] was used to plot the regression line:

$$f(N) = \frac{\alpha_v}{\beta(S_i)} \cdot \left(\frac{N_i - \xi(S_i)}{\beta(S_i)} \right) \exp \left[- \left(\frac{N_i - \xi(S_i)}{\beta(S_i)} \right)^{\alpha_v} \right], \quad (1)$$

where:

α_v the shape parameter,

$\beta(S_i)$ the scale parameter $10^{m \cdot \log(S) + b}$,

$\xi(S_i)$ the location parameter $10^{n \cdot \log(S) + d}$,

b constant term in an S–N curve equation,

d constant term in an S–N curve equation in the location parameter,

m scale coefficient in an S–N curve equation,

n scale coefficient in an S–N curve equation in the location parameter.

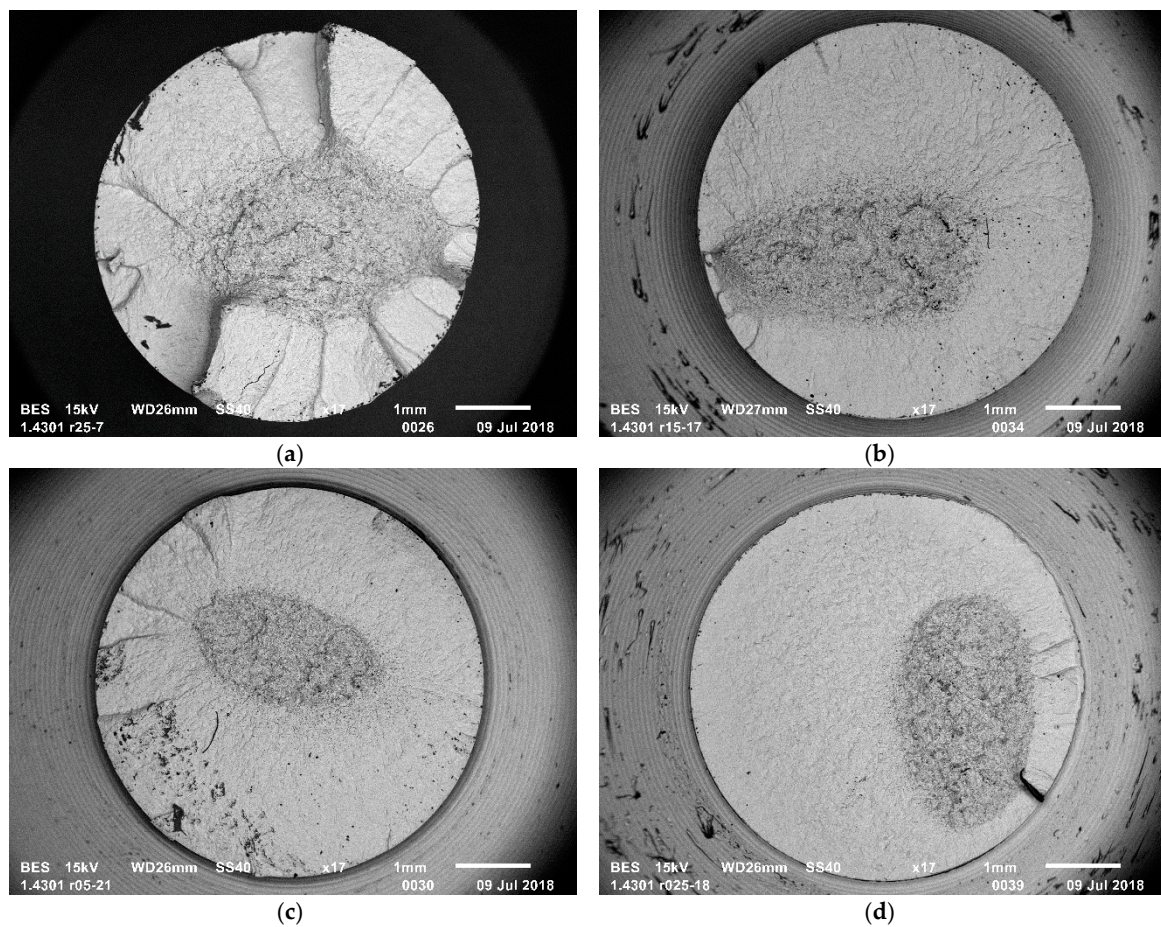


Figure 5. Fatigue fracture of specimen (a) smooth; (b) notched $r = 1.5$; (c) notched $r = 0.5$; (d) notched $r = 0.25$.

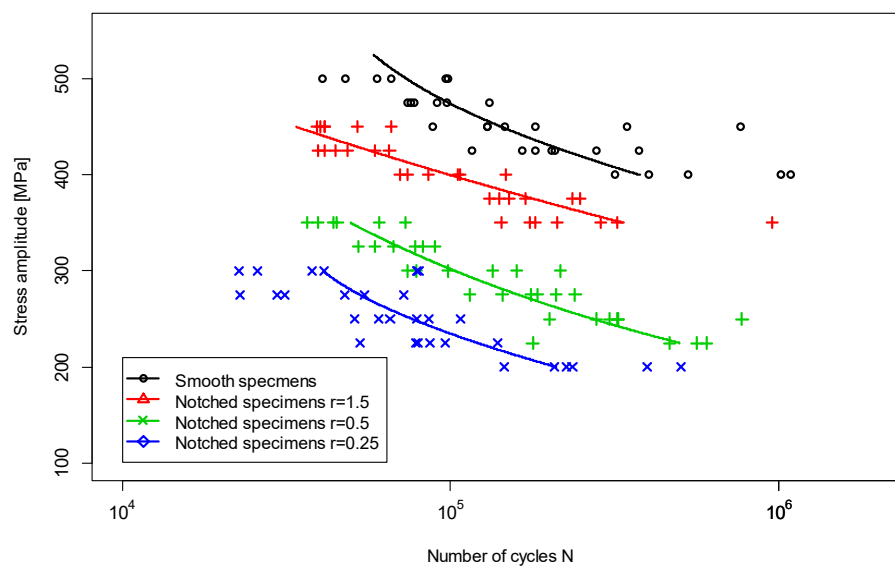


Figure 6. S–N curves for 1.4301 steel.

Table 4 shows the values of the coefficients estimated using Equation (1). A maximum likelihood method was used to determine the Equation (1) parameters. A method used to determine the S–N curve was discussed in [15,16,32–34]. The calculations were carried out using R software version 3.5.1 [35]. Figure 7 shows the S–N curves for 5% and 95% failure probability to highlight the different

ranges of scatter of test results for different sample geometries. A solid line shows the S–N curve at 50% failure probability.

Table 4. Value of linear regression parameters for the 1.4301 steel.

Geometry of Specimen	r , [mm]	α_v	m	b	n	d
Smooth	25	1.21	−10.2	32.1	−1.08	7.52
Notched	1.5	2.32	−9.2	28.9	−2.72	2.24
	0.5	1.27	−7.2	22.6	−3.54	13.57
	0.25	2.16	−4.9	16.7	2.83	−2.89

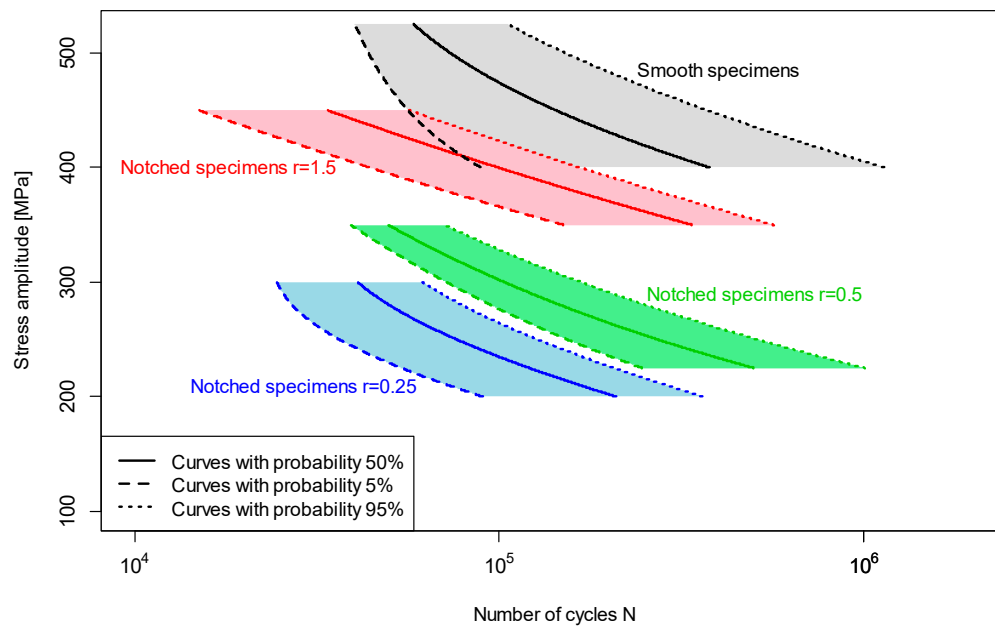


Figure 7. S–N curves for 1.4301 steel with 5% and 95% probability of failure.

To verify the scatter of fatigue life, the coefficient of variation was calculated and expressed following [15]:

$$V = \frac{\sigma_x}{\mu_x} \cdot 100\%, \quad (2)$$

$$\sigma_x = \sqrt{\beta(S_i)^2 \cdot \left[\Gamma\left(1 + \frac{2}{\alpha_v}\right) - \Gamma\left(1 + \frac{1}{\alpha_v}\right)^2 \right]}, \quad (3)$$

where:

V the coefficient of variation

Γ gamma function

σ_x standard deviation of the 3-parameter Weibull distribution for 105 cycles

μ_x expected value of the 3-parameter Weibull distribution for 105 cycles.

Figure 8 shows the calculation results. The graph also includes a regression line plotted using the following equation:

$$V = 22.9 K_t^2 - 90.9 K_t + 129. \quad (4)$$

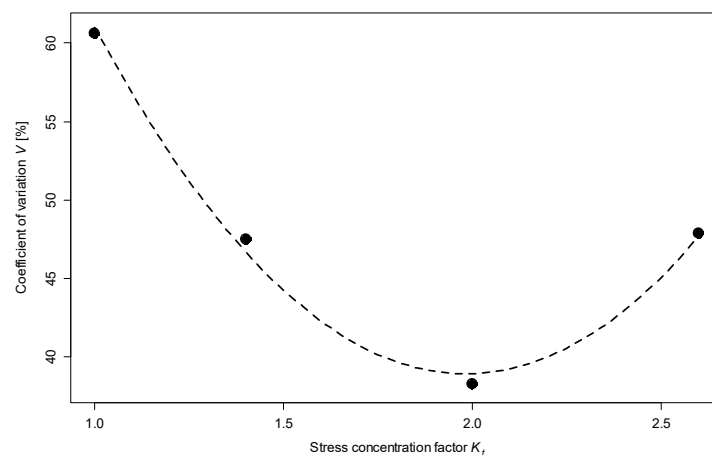


Figure 8. Relationship of variation to stress concentration factor.

4. Discussion

The test results show that the scatter of results depends on the sample geometry, as seen in Figures 7 and 8. The test results for 1.4301 stainless steel are similar to the results obtained for AW 6063 T6 aluminium alloy, presented in [36]. The linear regression Equation (4) shows that the lowest scatter of results is observed for the shape factor of 2. A similar value was obtained for AW 6063, as seen in [36]. The notch radius of the specimens was made with an accuracy of 0.01 mm. The precision of the notch radius, with this accuracy of production, is insignificant for smooth specimens and those with a notch radius equal to 1.5 mm and 0.5 mm. However, for the specimen with a radius of 0.25 mm, this accuracy of production influences the stress concentration factor, which can be 2.61 or 2.59 for a radius equal to 0.26 mm or 0.24 mm, respectively. The difference can be ± 2 MPa for theoretical stress in the root of the notch for nominal stress equal to 200 MPa.

The test results are crucial in the design of new machine components. The required failure probability of the bogie frame of a railway vehicle must not exceed 5% in accordance with [37]. A lower reliability coefficient can be calculated using Equation [8] (pp. 179–180) and a variance calculated from Equation (4), to reduce the amount of material required.

The scatter of fatigue life is lower for notched specimens because smooth specimens have a larger, highly stressed volume. This phenomenon can be explained by the weakest link theory presented by Weibull [38].

The change in fatigue life scatter was also observed when using a salt solution. The test results showing the effects of a corrosive agent on fatigue life and scatter of results for low-carbon 0.26% C steel are presented in [39]. For smooth samples in the air at room temperature, the fatigue life determination error was 4%, whereas, for the samples in 3.5% KCl and 5.5% KCl solution, the error was 1% and 1.5%, respectively. It clearly shows that each factor affecting the fatigue life also affects the scatter of results—a fact verified in the studies, in which the authors attempted to explain the scatter of fatigue life results by the presence of material defects, e.g., [40–44]. The studies correlate the fatigue life scatter with a random size and distribution of material defects.

5. Conclusions

The following conclusions can be drawn based on the results:

- notched samples feature lower fatigue life scatter than smooth samples,
- increase in the stress concentration factor decreases the scatter of results,
- an increase in the scatter of fatigue life was observed for samples with $K_t = 2.6$, explained by the higher sensitivity of notched samples to the accuracy of sample preparation techniques,
- which can be further explained by a different load gradient for a specific sample geometry, which in turn should be verified in further studies.

Author Contributions: Conceptualization, P.S. and A.M.; methodology, P.S.; A.M. and T.T.; software, P.S. and J.M.; validation, P.S.; formal analysis, P.S.; J.M. and T.T.; writing—original draft preparation, P.S.; M.S. and T.T.; writing—review and editing, P.S.; M.S. and A.M.; visualization, P.S. and M.S.; supervision, J.M. and A.M.

Funding: The research for this article was financially supported by the National Science Centre, project no. DEC-2017/01/X/ST8/00562.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Forum, I.S.S. *Global Consolidation Stainless Steel Cold All Products Consumption Index*. International Stainless Steel. Available online: http://www.worldstainless.org/Files/issf/non-image-files/PDF/statistics/190527_SCF_Public.pdf (accessed on 27 May 2019).
2. International Stainless Steel Forum Stainless Steel in Figures 2019; International Stainless Steel. Available online: http://www.worldstainless.org/Files/issf/non-image-files/PDF/ISSF_Stainless_Steel_in_Figures_2019_English_public_version.pdf (accessed on 27 May 2019).
3. Mohd, S.; Bhuiyan, M.S.; Nie, D.; Otsuka, Y.; Mutoh, Y. Fatigue strength scatter characteristics of JIS SUS630 stainless steel with duplex S-N curve. *Int. J. Fatigue* **2015**, *82*, 371–378. [CrossRef]
4. Akita, M.; Nakajima, M.; Uematsu, Y.; Tokaji, K.; Jung, J.-W. Some factors exerting an influence on the coxing effect of austenitic stainless steels. *Fatigue Fract. Eng. Mater. Struct.* **2012**, *35*, 1095–1104. [CrossRef]
5. Brnic, J.; Turkalj, G.; Canadija, M.; Lanc, D.; Krscanski, S.; Brcic, M.; Li, Q.; Niu, J. Mechanical properties, short time creep, and fatigue of an austenitic steel. *Materials* **2016**, *9*, 298. [CrossRef] [PubMed]
6. Jiang, H.; Han, K.; Li, D.; Cao, Z. Microstructure and Mechanical Properties Investigation of the CoCrFeNiNbX High Entropy Alloy Coatings. *Crystals* **2018**, *8*, 409. [CrossRef]
7. Tomaszewski, T. Analysis of the statistical size effect model with a critical volume in the range of high-cycle fatigue. *Proced. Struct. Integr.* **2018**, *13*, 1756–1761. [CrossRef]
8. Lee, Y.L.; Paw, J.; Hathaway, R.B.; Barkey, M.E. *Fatigue Testing and Analysis—Theory and Practice*; Elsevier Butterworth-Heinemann: Oxford, UK, 2005; ISBN 978-0-7506-7719-6.
9. Ai, Y.; Zhu, S.P.; Liao, D.; Correia, J.A.F.O.; De Jesus, A.M.P.; Keshtegar, B. Probabilistic modelling of notch fatigue and size effect of components using highly stressed volume approach. *Int. J. Fatigue* **2019**, *127*, 110–119. [CrossRef]
10. Strzelecki, P.; Sempruch, J.; Nowicki, K. Comparing guidelines concerning construction of the S-N curve within limited fatigue life range. *Polish Marit. Res.* **2015**, *22*, 67–74. [CrossRef]
11. Kurek, M.; Lagoda, T.; Katzy, D. Comparison of Fatigue Characteristics of some Selected Materials. *Mater. Test.* **2014**, *56*, 92–95. [CrossRef]
12. ASTM E-739-91. *Standard Practice for Statistical Analysis of Linear or Linearized Stress-Life (S-N) and Strain-Life (ϵ -N) Fatigue Data*; ASTM International: West Conshohocken, PA, USA, 2015.
13. ISO-12107. *Metallic Materials—Fatigue Testing—Statistical Planning and Analysis of Data*; ISO: Geneva, Switzerland, 2012.
14. Loren, S. Fatigue limit estimated using finite lives. *Fatigue Fract. Eng. Mater. Struct.* **2003**, *26*, 757–766. [CrossRef]
15. Rinne, H. *The Weibull Distribution*; Chapman and Hall/CRC: Boca Raton, FL, USA, 2008; ISBN 9780429142574.
16. Strzelecki, P.; Tomaszewski, T. Application of Weibull distribution to describe S-N curve with using small number specimens. *AIP Conf. Proc.* **2016**, *1780*, 020007.
17. Klemenc, J.; Fajdiga, M. Estimating S-N curves and their scatter using a differential ant-stigmergy algorithm. *Int. J. Fatigue* **2012**, *43*, 90–97. [CrossRef]
18. Topoliński, T.; Cichański, A.; Mazurkiewicz, A.; Nowicki, K. Fatigue Energy Dissipation in Trabecular Bone Samples with Stepwise-Increasing Amplitude Loading*. *Mater. Test.* **2011**, *53*, 344–350. [CrossRef]
19. Strzelecki, P.; Sempruch, J. Verification of analytical models of the S-N curve within limited fatigue life. *J. Theor. Appl. Mech.* **2016**, *54*, 63. [CrossRef]
20. Schijve, J. *Fatigue of Structures and Materials*, 2nd ed.; Springer Science+Business Media: Berlin, Germany, 2009; ISBN 978-1-4020-6807-2.
21. EN 10088-1. *Stainless Steels—Part 1: List of Stainless Steels Aciers*; CEN: Brussels, Belgium, 2014.

22. PN-EN 10278. *Dimensions and Tolerances of Bright Steel Products*; Polish Committee for Standardization: Warsaw, Poland, 2003.
23. PN-EN ISO 6892-1:2016. *Metallic Materials—Tensile Testing—Part. 1: Method of Test at Room Temperature*; Polish Committee for Standardization: Warsaw, Poland, 2016.
24. Boroński, D.; Kotyk, M.; Maćkowiak, P.; Śniezek, L. Mechanical properties of explosively welded AA2519-AA1050-Ti6Al4V layered material at ambient and cryogenic conditions. *Mater. Des.* **2017**, *133*, 390–403. [[CrossRef](#)]
25. Strzelecki, P.; Sempruch, J. Experimental Verification of the Analytical Method for Estimated S-N Curve in Limited Fatigue Life. *Mater. Sci. Forum* **2012**, *726*, 11–16. [[CrossRef](#)]
26. ISO-1143. *Metallic Materials—Rotating Bar Bending Fatigue Testing*; ISO: Geneva, Switzerland, 2010.
27. EN 10088-3. *Stainless Steels—Part 3: Technical Delivery Conditions for Semi-Finished Products, Bars, Rods, Wire, Sections and Bright Products of Corrosion Resisting Steels for General Purposes*; DIN: Berlin, Germany, 2005.
28. EN 10088-4. *Stainless Steels—Part 4: Technical Delivery Conditions for Sheet/Plate and Strip of Corrosion Resisting Steels for Construction Purposes*; BSI: London, UK, 2010.
29. ASTM E-112-12. *Standard Test. Methods for Determining Average Grain Size*; ASTM International: West Conshohocken, PA, USA, 2012.
30. Kocańda, S.; Szala, J. *Basis of Calculation of Fatigue*; Wydawnictwo Naukowe PWN: Warsaw, Poland, 1997. (In Polish)
31. Weibull, W. *A Statistical Representation of Fatigue Failures in Solids*; Elanders boktr.: Stockholm, Sweden, 1949.
32. Ling, J.; Pan, J. A maximum likelihood method for estimating P-S-N curves. *Int. J. Fatigue* **1997**, *19*, 415–419. [[CrossRef](#)]
33. Strzelecki, P.; Tomaszewski, T.; Sempruch, J. A method for determining a complete S-N curve using maximum likelihood. In *Proceedings of the 22nd International Conference on Engineering Mechanics*, Svratka, Czech Republic, 9–12 May 2016; Zolotarev, I., Radolf, V., Eds.; Institute of Thermomechanics of the Czech Academy of Sciences: Svratka, Czech Republic, 2016; pp. 530–533.
34. Pollak, R.D.; Palazotto, A.N. A comparison of maximum likelihood models for fatigue strength characterization in materials exhibiting a fatigue limit. *Probab. Eng. Mech.* **2009**, *24*, 236–241. [[CrossRef](#)]
35. R Core Team R: *A Language and Environment for Statistical Computing*; R Core Team R: Vienna, Austria, 2015.
36. Strzelecki, P. Scatter of fatigue life regarding stress concentration factor. *Proced. Struct. Integr.* **2018**, *13*, 631–635. [[CrossRef](#)]
37. PN-EN 13749 *Railway Applications—Wheelsets and Bogies—Method of Specifying the Structural Requirements of Bogie Frames*; CEN: Brussels, Belgium, 2011.
38. Weibull, W. *A Statistical Theory of the Strength of Materials*; Generalstabens litografiska anstalts förlag: Stockholm, Sweden, 1939; p. 151.
39. Gope, P.C. Scatter analysis of fatigue life and prediction of S-N curve. *J. Fail. Anal. Prev.* **2012**, *12*, 507–517. [[CrossRef](#)]
40. Zheng, X.; Engler-Pinto, C.; Su, X.; Cui, H.; Wen, W. Correlation between Scatter in Fatigue Life and Fatigue Crack Initiation Sites in Cast Aluminum Alloys. *SAE Int. J. Mater. Manuf.* **2012**, *5*, 270–276. [[CrossRef](#)]
41. Mohd, S.; Mutoh, Y.; Otsuka, Y.; Miyashita, Y.; Koike, T.; Suzuki, T. Scatter analysis of fatigue life and pore size data of die-cast AM60B magnesium alloy. *Eng. Fail. Anal.* **2012**, *22*, 64–72. [[CrossRef](#)]
42. Siqueira, A.F.; Baptista, C.A.R.P.; Molent, L. On the determination of a scatter factor for fatigue lives based on the lead crack concept. *J. Aerosp. Technol. Manag.* **2013**, *5*, 223–230. [[CrossRef](#)]
43. Ai, Y.; Zhu, S.P.; Liao, D.; Correia, J.A.F.O.; Souto, C.; De Jesus, A.M.P.; Keshtegar, B. Probabilistic modeling of fatigue life distribution and size effect of components with random defects. *Int. J. Fatigue* **2019**, *126*, 165–173. [[CrossRef](#)]
44. Murakami, Y. Material defects as the basis of fatigue design. *Int. J. Fatigue* **2012**, *41*, 2–10. [[CrossRef](#)]

