

Metal Fatigue: Effects of Small Defects and Nonmetallic Inclusions

Second Edition

Yukitaka Murakami

Emeritus Professor, Kyushu University, Japan



ACADEMIC PRESS

An imprint of Elsevier

Contents

Preface to the second edition	xvii
Preface to the first edition	xxi
1 Mechanism of fatigue in the absence of defects and inclusions	1
1.1 What is a fatigue limit?	1
1.1.1 Steels	1
1.1.2 Nonferrous metals	4
1.2 Relationship between static strength and fatigue strength	5
References	9
2 Stress concentration	13
2.1 Stress concentrations at holes and notches	13
2.2 Stress concentration at a crack	17
2.2.1 'area' as a new geometrical parameter	19
2.2.2 Effective 'area' for particular cases	19
2.2.3 Cracks at stress concentrations	21
2.2.4 Interaction between two cracks	24
2.2.5 Interaction between a crack and a free surface	25
References	26
3 Notch effect and size effect	29
3.1 Notch effect	29
3.1.1 Effect of stress distribution at notch roots	29
3.1.2 Nonpropagating cracks at notch roots	31
3.2 Size effect	35
References	36
4 Effect of size and geometry of small defects on the fatigue limit	39
4.1 Introduction	39
4.2 Influence of extremely shallow notches or extremely short cracks	39
4.3 Fatigue tests on specimens containing small artificial defects	41
4.3.1 Effect of small artificial holes having the diameter d equal to the depth h	41
4.3.2 Effect of small artificial holes having different diameters and depths	46
4.4 Critical stress for fatigue crack initiation from a small crack	52
References	58

5	Effect of hardness H_V on fatigue limits of materials containing defects, and fatigue limit prediction equations	61
5.1	Relationship between ΔK_{th} and the geometrical parameter, \sqrt{area}	61
5.2	Material parameter H_V which controls fatigue limits	64
5.3	Application of the prediction equations	66
5.4	Limits of applicability of the prediction equations	73
5.5	The importance of the finding that specimens with an identical value of \sqrt{area} for small holes or small cracks have identical fatigue limits: when the values of \sqrt{area} for a small hole and a small crack are identical, are the fatigue limits for specimens containing these two defect types really identical?	73
5.6	Effect of orientation of small defects on the fatigue limit of steels	79
5.7	Fatigue limit prediction for a small defect at a notch root	85
5.8	Summary of the \sqrt{area} parameter model	87
	References	91
6	Effects of nonmetallic inclusions on fatigue strength	95
6.1	Review of existing studies and current problems	95
6.1.1	Correlation of material cleanliness and inclusion rating with fatigue strength	95
6.1.2	Size and location of inclusions and fatigue strength	97
6.1.3	Mechanical properties of microstructure and fatigue strength	100
6.1.4	Influence of nonmetallic inclusions related to the direction and mode of loading	101
6.1.5	Inclusion problem factors	103
6.2	Similarity of effects of nonmetallic inclusions and small defects and a unifying interpretation	105
6.3	Quantitative evaluation of effects of nonmetallic inclusions: strength prediction equations and their application	110
6.4	Causes of fatigue strength scatter for high-strength steels and scatter band prediction	114
6.5	Effect of mean stress	120
6.5.1	Quantitative evaluation of the mean stress effect on fatigue of materials containing small defects	121
6.5.2	Effects of both nonmetallic inclusions and mean stress in hard steels	125
6.5.3	Prediction of the lower bound of scatter and its application	130
6.6	Estimation of maximum inclusion size \sqrt{area}_{max} by microscopic examination of a microstructure	133
6.6.1	Measurement of \sqrt{area}_{max} for largest inclusions by optical microscopy	133

6.6.2	True and apparent maximum sizes of inclusions	136
6.6.3	Two-dimensional prediction method for largest inclusion size and evaluation by numerical simulation	139
	References	144
7	Bearing steels	151
7.1	Influence of steel processing	152
7.2	Inclusions at fatigue fracture origins	153
7.3	Cleanliness and fatigue properties	156
7.3.1	Total oxygen (O) content	158
7.3.2	Ti content	159
7.3.3	Ca content	159
7.3.4	Sulphur (S) content	160
7.4	Fatigue strength of superclean bearing steels and the role of nonmetallic inclusions	162
7.5	Tessellated stresses associated with inclusions: thermal residual stresses around inclusions	167
7.6	What happens to the fatigue limit of bearing steels without nonmetallic inclusions?—Fatigue strength of electron beam remelted superclean bearing steel	171
7.6.1	Material and experimental procedure	173
7.6.2	Inclusion rating based on the statistics of extremes	176
7.6.3	Fatigue test results	177
7.6.4	The true character of small inhomogeneities at fracture origins	180
	References	183
8	Spring steels	187
8.1	Spring steels (SUP12) for automotive components	187
8.2	Explicit analysis of nonmetallic inclusions, shot peening, decarburised layers, surface roughness, and corrosion pits in automobile suspension spring steels	192
8.2.1	Materials and experimental procedure	193
8.2.2	Interaction of factors influencing fatigue strength	197
8.3	Mechanism of creation of residual stress by shot peening: a typical misconception and reality	207
8.3.1	Materials and method of experiment	208
8.3.2	Residual stress by a single shot	209
8.3.3	Superposition of residual stresses by the second shot	209
8.3.4	Residual stresses by multiple shots	212
8.3.5	Rotating-bending fatigue test of a specimen after a single shot	215
	References	217

9	Tool steels: effect of carbides	219
9.1	Low-temperature forging and microstructure	219
9.2	Static strength and fatigue strength	221
9.3	Relationship between carbide size and fatigue strength	224
	References	226
10	Effects of shape and size of artificially introduced alumina particles on 1.5Ni–Cr–Mo (En24) steel	227
10.1	Artificially introduced alumina particles with controlled sizes and shapes, specimens and test stress	227
10.2	Rotating bending fatigue tests without shot peening	230
10.3	Rotating bending fatigue tests on shot-peened specimens	232
10.4	Tension compression fatigue tests	238
	References	238
11	Nodular cast iron and powder metal	239
11.1	Introduction	239
11.2	Fatigue strength prediction of nodular cast irons by considering graphite nodules to be equivalent to small defects	240
11.3	Parameters to be considered for fatigue limit predictions	249
11.3.1	Nature of fatigue limit of NCI	249
11.3.2	Fatigue limit prediction method for NCI specimens containing small defects	250
11.3.3	Prediction of the fatigue limit of smooth specimens and the influence of microshrinkage cavities	256
11.4	Powder metal: effects of pores and microstructures	259
11.4.1	Materials and experimental procedures	260
11.4.2	Microstructure	260
11.4.3	Fatigue cracks	262
11.4.4	Effect of the size of Fe particles on fatigue strength	263
	References	265
12	Influence of Si-phase on fatigue properties of aluminium alloys	269
12.1	Materials, specimens and experimental procedure	269
12.2	Fatigue mechanism	269
12.2.1	Continuously cast material	271
12.2.2	Extruded material	273
12.2.3	Fatigue behaviour of specimens containing an artificial hole	273
12.3	Mechanisms of ultralong fatigue life	279
12.4	Low-cycle fatigue	283
12.4.1	Fatigue mechanism	283
12.4.2	Continuously cast material	284
12.4.3	Extruded material	284
12.4.4	Comparison with high-cycle fatigue	284
12.4.5	Cyclic property characterisation	287

12.5	Summary	291
	References	291
13	Ti alloys	293
13.1	General nature of fatigue fracture origin in Ti alloys	293
13.2	Very high cycle fatigue (VHCF) properties of Ti-6Al-4V alloy	296
13.3	Effects of notches and burrs on high cycle fatigue of Ti-6Al-4V	306
13.3.1	Introduction	306
13.3.2	Test specimen and experimental method for notch effect test	307
13.3.3	Fatigue limit and the \sqrt{area} parameter model	308
13.3.4	Crack initiation and nonpropagating cracks	309
13.3.5	Effect of a burr beside a drilled hole	311
	References	314
14	Torsional fatigue	317
14.1	Introduction	317
14.2	Effect of small artificial defects on torsional fatigue strength	318
14.2.1	Ratio of torsional fatigue strength to bending fatigue strength	318
14.2.2	The state of nonpropagating cracks at the torsional fatigue limit	323
14.2.3	Torsional fatigue of high carbon Cr bearing steel	326
14.3	Effects of small cracks	329
14.3.1	Material and test procedures	329
14.3.2	Fatigue test results	331
14.3.3	Crack initiation and propagation from precracks	331
14.3.4	Fracture mechanics evaluation of the effect of small cracks on torsional fatigue	334
14.3.5	Prediction of torsional fatigue limit by the \sqrt{area} parameter model	336
	References	339
15	The mechanism of fatigue failure in the very high cycle fatigue (VHCF) life regime of $N > 10^7$ cycles	341
15.1	Mechanism of elimination of conventional fatigue limit: influence of hydrogen trapped by inclusions	341
15.1.1	Method of data analysis	342
15.1.2	Material, specimens and experimental method	343
15.1.3	Distribution of residual stress and hardness	344
15.1.4	Fracture origins	344
15.1.5	$S-N$ curves	344
15.1.6	Details of fracture surface morphology and influence of hydrogen	347

15.2	Fractographic investigation	359
15.2.1	Measurement of surface roughness	360
15.2.2	The outer border of a fish eye	361
15.2.3	Crack growth rate and fatigue life	366
15.3	Conclusions when the first edition of this book was published	368
15.4	Mechanism of very high cycle fatigue (VHCF) and fatigue design	370
15.4.1	Mechanics of small cracks and VHCF	370
15.4.2	Interpretation of VHCF data and mechanism of elimination of fatigue threshold	373
15.4.3	Mechanism of fatigue failure originating at nonmetallic inclusions and fatigue life prediction models	381
15.4.4	Fatigue life prediction model	391
15.4.5	Applications to fatigue life prediction	393
15.4.6	Summary and perspectives	395
15.5	Statistical nature of VHCF failure at facets	396
	References	400
16	Effect of surface roughness on fatigue strength	407
16.1	Introduction	407
16.2	Material and experimental procedure	408
16.2.1	Material	408
16.2.2	Introduction of artificial surface roughness and of a single notch	408
16.2.3	Measurement of hardness and surface roughness	412
16.3	Results and discussion	414
16.3.1	Results of fatigue tests	414
16.3.2	Quantitative evaluation by the $\sqrt{\text{area}}$ parameter model	414
16.4	Guidance for fatigue design engineers	421
16.5	Effect of surface scratch in torsional fatigue of spring steel	422
16.5.1	Experiment	422
16.5.2	Fatigue strength of smooth specimens	424
16.5.3	Effects of scratches on the fatigue strength	425
	References	429
17	Martensitic stainless steels	431
17.1	Materials and experimental procedure	431
17.2	Influence of inherent defects on the fatigue strength	434
17.2.1	Fatigue tests on smooth specimens with failure from nonmetallic inclusion	434
17.2.2	Estimation of the lower bound of the fatigue limit using the statistics of extremes	439
17.3	Influence of various types of small defects on the fatigue strength	440
17.3.1	Test results on precipitation hardened 17-4PH stainless steel	440

17.3.2	Test results on martensitic 12% Cr stainless steel X20Cr13	445
17.3.3	Test results for martensitic 12% Cr stainless steel AISI403	446
17.4	Effect of mean stress	447
17.4.1	Quantitative evaluation of the mean stress effect for 17-4PH steel	448
17.4.2	Quantitative evaluation of the mean stress effect of AISI403 steel	449
	References	450
18	Additive manufacturing: effects of defects	453
18.1	Ti–6Al–4V	454
18.2	Tests, results and discussion for Ti–6Al–4V	457
18.3	Nickel-based superalloy 718	467
18.4	Tests, results and discussion for nickel-based superalloy 718	468
18.5	Summary and perspectives	477
18.5.1	Defects	477
18.5.2	Goal to ideal fatigue strength	478
18.5.3	Standardisation of defect size	479
18.5.4	Surface effect	479
18.5.5	Quality control of AM components	479
	References	480
	Appendix A: High probability of fatigue fracture from surface defects due to difference of stress intensity factor for surface cracks and subsurface cracks	481
19	Fatigue threshold in Mode II and Mode III, ΔK_{IIth} and ΔK_{IIIth}, and small crack problems	485
19.1	Method of measurement for ΔK_{IIth}	486
19.1.1	Basic model	486
19.1.2	Experimental method	487
19.2	Results and discussion	489
19.2.1	Variation of electric potential	489
19.2.2	Fracture surfaces	490
19.2.3	Relationship between da/dN and ΔK_{II}	490
19.2.4	The values of ΔK_{IIth} for various steels	492
19.3	Fatigue crack growth mechanism under Mode III loadings: measurement of ΔK_{IIIth}	492
19.3.1	Material and test method for Mode III fatigue crack growth	492
19.3.2	Fatigue crack growth mechanism under Mode III loading	493
19.3.3	Crack path and mechanism of factory-roof formation under Mode III loading	494

19.4	Mutual relationship of ΔK_{Ith} , ΔK_{IIth} and ΔK_{IIIth} and mechanism of factory-roof morphology: summary	498
19.5	Mode II threshold stress intensity factors ΔK_{IIth} and ΔK_{IIIth} for small cracks: crack size dependence	499
19.5.1	Test method for investigating shear-mode fatigue crack threshold in hard steels	499
19.5.2	Effect of crack-face interference on ΔK_{IIth}	500
19.5.3	Crack size dependence for ΔK_{IIth}	503
19.5.4	Approximate expression of stress intensity factor for shear-mode crack by means of $\sqrt{\text{area}}$	506
19.5.5	Estimation of the threshold SIF ranges, ΔK_{rth} by means of the $\sqrt{\text{area}}$ parameter model	510
19.5.6	The influence of static crack-opening stress on the threshold SIF for shear-mode fatigue crack growth	512
19.6	Effect of crack branching on fatigue life and the reason for unsuccessful results of Miner's rule in mixed-mode fatigue	516
19.6.1	Experimental procedure	517
19.6.2	Reversed torsion and combined push–pull/torsion fatigue tests	518
	References	524
20	Contact fatigue	529
20.1	Nature of rolling contact fatigue	529
20.2	Experimental and fracture mechanics study of the pit formation mechanism under repeated lubricated rolling–sliding contact	533
20.2.1	Experimental method	534
20.2.2	Experimental results	535
20.2.3	Fracture mechanics analysis	540
20.3	Role of inclusions, surface roughness and operating conditions on rolling contact fatigue	544
20.4	Examples of contact fatigue failures and their interpretation from the viewpoint of the rolling contact fatigue experiment	547
20.4.1	Dark-spot defects in railway rails	549
20.4.2	Fracture originating from subsurface nonmetallic inclusions in railway rails	549
20.4.3	Spalling of steel making backup rolls	552
20.4.4	Spalling of steel making work roll	556
20.5	Rolling contact fatigue strength of bearing steel analysed as small crack problems	558
	References	563
21	Hydrogen embrittlement	567
21.1	Effect of hydrogen on loss of ductility in tensile tests	568

21.2	Effects of hydrogen charge on the formation of cyclic slip bands in fatigue of annealed carbon steels	568
21.2.1	Materials, specimens and experimental methods	570
21.2.2	Effects of hydrogen on slip band morphology and crack initiation near the fatigue limit stress	571
21.3	Effects of hydrogen charge on the mechanism of fatigue crack growth of low-strength steels	576
21.3.1	Fatigue crack growth behaviour of a pipeline steel	576
21.4	Effect of hydrogen on fatigue behaviour of a Cr–Mo steel SCM435	580
21.5	Effect of hydrogen on fatigue behaviour of austenitic stainless steels	581
21.5.1	Basic parameters: hydrogen content, diffusion coefficient, fatigue crack growth and test frequency	581
21.5.2	What happens if nondiffusible hydrogen is removed by a special heat treatment?	587
21.5.3	Hydrogen-induced striation formation mechanism	589
21.5.4	Case study: dispenser hose fatigue failure at a hydrogen station	590
21.5.5	Hydrogen effect against hydrogen embrittlement	592
21.6	Hydrogen embrittlement of other materials	599
21.6.1	High-strength steels	599
21.6.2	Aluminium alloys	602
	References	604
22	A new nonmetallic inclusion rating method by the positive use of the hydrogen embrittlement phenomenon	609
22.1	Introduction	609
22.2	Materials and experimental methods	611
22.2.1	Materials and specimens	611
22.2.2	Hydrogen-precharged method (H-precharged method)	611
22.2.3	Nonmetallic inclusion rating by tensile testing with hydrogen-precharged specimen: HE method	612
22.2.4	Nonmetallic inclusion rating by fatigue testing	615
22.2.5	Nonmetallic inclusion rating methods using an optical microscope	616
22.2.6	Size measurement and identification of inclusions	616
22.3	Results and discussion	617
22.3.1	Inclusion rating by the hydrogen embrittlement method	617
22.3.2	Inclusion rating method by fatigue test using SAE52100 steel	631
22.3.3	Inclusion rating method by optical microscopy	634
22.3.4	Inclusion inspection method in the case of bilinear statistics of extremes	636

22.4	Summary and perspective	638
22.4.1	Summary	638
22.4.2	Perspective	639
	References	641
23	What is fatigue damage? A viewpoint from the observation of a low-cycle fatigue process	643
23.1	Introduction	643
23.2	Fatigue damage in low-cycle fatigue and the behaviour of small cracks	644
23.2.1	Material and test procedure	644
23.2.2	Experimental results and discussion	645
23.3	Ductility loss during the fatigue process	657
23.3.1	Effects of small surface cracks on ductility loss during low-cycle fatigue	657
23.3.2	Material and test procedure	658
23.3.3	Results and discussion	660
23.4	Experimental conclusions	666
23.5	Summary in terms of the correlation among fatigue damage, small cracks, Coffin–Manson law and ductility loss	666
	References	667
24	Quality control of mass production components based on defect analysis	669
24.1	Introduction	669
24.2	The importance of prediction of the extreme value based on the statistics of extremes	670
24.3	Prevention method for recalls	673
24.3.1	How to find the cause of failure and the method of statistics extremes analysis	673
24.3.2	Statistics of extremes data of defects as failure cause and its applications to fatigue design	674
24.3.3	Practical applications to design and quality control based on the statistics of extremes	675
24.4	Basic concept and guide for the application of the statistics of extremes method	682
24.4.1	What is the appropriate parameter?	682
24.4.2	Reconsideration of the stress–strength model	682
24.4.3	Applications to large-scale but a small number of production machinery	683
24.5	Conclusions	684
	References	684
	Appendix: Definition of the control volume as the potential risk volume under high applied stress	686

Appendix A: Instructions for a new method of inclusion rating and correlations with the fatigue limit	689
Appendix B: Database of statistics of extreme values of inclusion size \sqrt{area}_{\max}	711
Appendix C: Probability sheets of statistics of extremes	717
Index	719