Contents

		to the first edition	xxi
1		chanism of fatigue in the absence of defects and inclusions	1
	1.1	What is a fatigue limit?	1
		1.1.1 Steels	1
	1.0	1.1.2 Nonferrous metals	4
		Relationship between static strength and fatigue strength	5
	KCI	cicinces	9
2	Str	ess concentration	13
	2.1	at Holob and Notolies	13
	2.2		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
	Ref	erences	26
3	Not	ch 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
	Refe	erences	36
4	Effe	ect of size and geometry of small defects on the fatigue limit	39
	4.1		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	The same of the sa	52
	Refe	erences	58

5	Eff	ect of h	pardness $H_{ m V}$ on fatigue limits of materials containing	
	def	ects, ar	nd fatigue limit prediction equations	61
	5.1	Relat	ionship between ΔK_{th} and the geometrical parameter, \sqrt{area}	61
	5.2	Mate	rial parameter $H_{\rm V}$ which controls fatigue limits	64
	5.3	Appl	ication of the prediction equations	66
	5.4	Limit	s of applicability of the prediction equations	73
	5.5	The i	mportance of the finding that specimens with an identical	
		value	of \sqrt{area} for small holes or small cracks have identical	
		fatigu	ie limits: when the values of \sqrt{area} for a small hole	
		and a	small crack are identical, are the fatigue limits for	
		speci	mens containing these two defect types really identical?	73
	5.6	Effec	t of orientation of small defects on the fatigue limit	
		of ste	els	79
	5.7	Fatig	ue limit prediction for a small defect at a notch root	85
	5.8	Sumn	nary of the \sqrt{area} parameter model	87
	Ref	erences	<u>Hali</u>	91
6	Effe	ects of i	nonmetallic inclusions on fatigue strength	95
			w of existing studies and current problems	95
		6.1.1	Correlation of material cleanliness and inclusion rating	
		er e	with fatigue strength	95
		6.1.2	Size and location of inclusions and fatigue strength	97
		6.1.3		
			strength	100
		6.1.4	Influence of nonmetallic inclusions related to the	100
			direction and mode of loading	101
		6.1.5	Inclusion problem factors	103
	6.2	Simila	arity of effects of nonmetallic inclusions and small	100
			s and a unifying interpretation	105
	6.3		itative evaluation of effects of nonmetallic inclusions:	100
			th prediction equations and their application	110
	6.4		s of fatigue strength scatter for high-strength steels	
			eatter band prediction	114
Ġ.	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	120
			application	130
	6.6	Estima	ation of maximum inclusion size \sqrt{area}_{max} by microscopic	150
		exami	nation of a microstructure	133
		6.6.1	Measurement of \sqrt{area}_{max} for largest inclusions	100
			by optical microscopy	133

	•	6.6.2 6.6.3	Two-dimensional prediction method for largest	136
	Ref	erences	inclusion size and evaluation by numerical simulation	139 144
7	Bea	ring ste	eels	151
	7.1	Influe	ence of steel processing	152
	7.2	Inclus	sions at fatigue fracture origins	153
	7.3	Clean	liness 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	Fatigu	e strength of superclean bearing steels and the role	
		of nor	nmetallic inclusions	162
	7.5	Tessel	llated stresses associated with inclusions: thermal	
		residu	al stresses around inclusions	167
	7.6		happens to the fatigue limit of bearing steels without	
		nonme	etallic inclusions?—Fatigue strength of electron beam	
			ted superclean bearing steel	171
		7.6.1	Material and experimental procedure	173
		7.6.2	9	176
		7.6.3	0	177
		7.6.4	The true character of small inhomogeneities at fracture	
			origins	180
	Refe	erences		183
8	Spr	ing stee	els	187
	8.1		g steels (SUP12) for automotive components	187
	8.2	Explic	cit analysis of nonmetallic inclusions, shot peening,	
			purised layers, surface roughness, and corrosion pits	
		in auto	omobile suspension spring steels	192
		8.2.1	Materials and experimental procedure	193
		8.2.2	Interaction of factors influencing fatigue strength	197
	8.3	Mecha	anism of creation of residual stress by shot peeing:	
		a typic	cal 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
	Refe	rences		217

າກກ	tents	

9	Too	l steels:	effect of carbides	21
	9.1	Low-te	emperature forging and microstructure	21
	92	Static	strength and fatigue strength	22
	9.3	Relatio	onship between carbide size and fatigue strength	22
		erences		22
10	Effe	cts of sl	nape and size of artificially introduced alumina	
	part	icles on	1.5Ni-Cr-Mo (En24) steel	22
	10.1		cially introduced alumina particles with controlled sizes	
			napes, specimens and test stress	22
			ng bending fatigue tests without shot peening	23
			ng bending fatigue tests on shot-peened specimens	23
			on compression fatigue tests	23
	Refe	rences		23
11	Nodu	ılar cası	t iron and powder metal	23
	11.1	Introd		23
	11.2	Fatigu	e strength prediction of nodular cast irons by considering	
		graphi	te nodules to be equivalent to small defects	24
	11.3		eters to be considered for fatigue limit predictions	24
		11.3.1	The same of the sa	249
		11.3.2	8 Proceed mothed for field specificing	
			containing small defects	250
		11.3.3	Prediction of the fatigue limit of smooth specimens	
		-	and the influence of microshrinkage cavities	256
	11.4	Powde	r metal: effects of pores and microstructures	259
		11.4.1	proceduros	260
			Microstructure	260
		11.4.3		262
	T. C	11.4.4	Effect of the size of Fe particles on fatigue strength	263
	Refer	ences		265
12	Influe	ence of S	Si-phase on fatigue properties of aluminium alloys	269
	12.1	Materia	als, specimens and experimental procedure	269
	12.2		mechanism	269
		12.2.1	Continuously cast material	271
			Extruded material	273
		12.2.3	Fatigue behaviour of specimens containing an artificial	
	10.0	3.6 1	hole	273
	12.3	Mechai	uisms of ultralong fatigue life	279
	12.4		cle 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

viii

Contents:	

		' Summa ences	ary	29 29
13	Ti all	lovs	•	29
	13.1	-	l nature of fatigue fracture origin in Ti alloys	29:
	13.2		igh cycle fatigue (VHCF) properties of Ti-6Al-4V alloy-	29
	13.3		of notches and burrs on high cycle fatigue of Ti-6Al-4V	
٠.		13.3.1	Introduction	30
		13.3.2	Test specimen and experimental method for notch	
			effect test	30
		13.3.3	Fatigue limit and the \sqrt{area} parameter model	30
	•	13.3.4		30
		13.3.5	Effect of a burr beside a drilled hole	31
	Refer	ences		314
14	Torsi	onal fat	igue	31′
	14.1	Introdu		31
	14.2	Effect of	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		of small cracks	329
		14.3.1	Material and test procedures	329
		14.3.2	Fatigue test results	33
		14.3.3	Crack initiation and propagation from precracks	33
		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
	Refer	ences		339
15	The n	nechanis	sm of fatigue failure in the very high cycle fatigue	
	(VHC		regime of $N > 10^7$ cycles	341
	15.1	Mechar	nism of elimination of conventional fatigue limit:	
			ce 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

	_			
- 1	Րɾ	m	tei	nt

18

19

tents			xi
	17.3.2	Test results on martensitic 12% Cr stainless	
	17.5.2	steel X20Cr13	445
	17.3.3	Test results for martensitic 12% Cr stainless	773
	17.0.0	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
Refe	rences		450
Addi	tive mar	nufacturing: effects of defects	453
18.1			454
18.2	Tests, 1	results and discussion for Ti-6Al-4V	457
18.3	Nickel-	-based superalloy 718	467
18.4	Tests, 1	results and discussion for nickel-based superalloy 718	468
18.5	Summa	ary and perspectives	477
	18.5.1	Defects	477
		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
	rences		480
		High probability of fatigue fracture from surface	
		difference of stress intensity factor for surface	
crack	s and sul	bsurface cracks	481
		hold in Mode II and Mode III, $\Delta K_{ m IIth}$ and $\Delta K_{ m IIIth}$,	
		ack problems	485
19.1		of measurement for $\Delta K_{\Pi th}$	486
		Basic model	486
10.0		Experimental method	487
19.2		and discussion	489
		Variation of electric potential	489
		Fracture surfaces	490
	19.2.3	Relationship between da/dN and ΔK_{II}	490
10.2	19.2.4	The values of ΔK_{Hth} for various steels	492
19.3		crack growth mechanism under Mode III loadings:	400
	19.3.1	ement of ΔK_{IIIth}	492
	17.J.1	Material and test method for Mode III fatigue	400
	19.3.2	crack growth Fatigue crack growth mechanism under Mode III	492
	17.5.2	loading	493
	19.3.3	Crack path and mechanism of factory-roof formation	793
		r r	

under Mode III loading

494

	15.2	Fracto	graphic investigation	35
		15.2.1	Measurement of surface roughness	36
		15.2.2	The outer border of a fish eye	36
		1523	Crack growth rate and fatigue life	36
	15.3	Conch	isions when the first edition of this book was published	36
	15.4	Mecha	nism 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	383
			Fatigue life prediction model	39:
			Applications to fatigue life prediction	393
			Summary and perspectives	395
	15.5	Statisti	cal nature of VHCF failure at facets	39€
	Refe	rences		400
16	Effec	t of surf	ace roughness on fatigue strength	407
	16.1	Introdu		407
	16.2	Materia	al and experimental procedure	408
			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		and discussion	414
			Results of fatigue tests	414
		16.3.2	Quantitative evaluation by the \sqrt{area} parameter model	414
	16.4	Guidan	ce for fatigue design engineers	421
	16.5	Effect of	of surface scratch in torsional fatigue of spring steel	422
			Experiment	422
		16.5.2	S S criticom obcomions	424
		16.5.3	Effects of scratches on the fatigue strength	425
	Refer	ences		429
17	Mart	ensitic st	tainless steels	431
	17.1	Materia	Is and experimental procedure	431
	17.2	Influence	ce 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	Influenc	ce of various types of small defects on the fatigue strength	440
		17.3.1	Test results on precipitation hardened 17-4PH stainless	
			steel	440

	19	.4 Mutual relationship of ΔK_{Ith} , ΔK_{Ith} 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 19.5.2 Effect of crack-face interference on ΔK_{-} .	499
			500
		19.5.3 Crack size dependence for ΔK_{Hith} 19.5.4 Approximate expression of stress intensity feature	503
		11 Stress of Stress Hitchstey (actor)	
		for shear-mode crack by means of \sqrt{area} 19.5.5 Estimation of the threshold SIE ranges. A K	506
		or the threshold off. ranges, $\Delta \Lambda_{mil}$ by	
		means of the \sqrt{area} parameter model 19.5.6 The influence of static crack opening stress are	510
		and of state clack-obeling stiess on	
	19.6	the threshold SIF for shear-mode fatigue crack growth	512
	17.0	brief of crack branching on fatigue life and the reason for	
		unsuccessful results of Miner's rule in mixed-mode fatigue	516
		13.0.1 Experimental procedure	517
		19.6.2 Reversed torsion and combined push—pull/torsion	
	Dof	fatigue tests	518
	Kele	rences	524
20	Con	tact fatigue	
			529
	20.2	Nature of rolling contact fatigue	529
	_0.2	T and fractate mechanics shint of the nit	
		formation mechanism under repeated lubricated	
		rolling—sliding contact	533
		20.2.1 Experimental method	534
		20.2.2 Experimental results 20.2.3 Fracture mechanics analysis	535
	20.3	and the character and the contract of the cont	540
	20.5		
	20.4	on rouning contact ratigue	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 Spaning of steel making backup rolls	552
	20.5	20.4.4 Spalling of steel making work roll	556
	20.5	Rolling Contact latigue strength of bearing steel analysed	_
	Dofor	as sman crack problems	558
	Refere	CHCCS	563
21	Hvdra	ogen embrittlement	
	21.1	Effect of hydrogen and a control of hydrogen	567
		Effect of hydrogen on loss of ductility in tensile tests	568

	21.2		of hydrogen charge on the formation of cyclic slip bands	
			que 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	
	01.2	T7.CC4-	crack initiation near the fatigue limit stress	571
	21.3		of hydrogen charge on the mechanism of fatigue	
			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 So		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	Hydrog	en embrittlement of other materials	599
		21.6.1	High-strength steels	599
		21.6.2	Aluminium alloys	602
	Refer	ences		604
22			etallic inclusion rating method by the positive	
			lrogen embrittlement phenomenon	609
	22.1	Introdu		609
	22.2		als and experimental methods	611
		22.2.1	<u>.</u>	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		and discussion	617
		22.3.1	Inclusion rating by the hydrogen embrittlement method	617
		22.3.2	Inclusion rating method by fatigue test using	4
		00.00	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

Contents		

_	•			Contents
	22.4	Sumn	nary and perspective	600
		22.4.1		638
		22.4.2	2 Perspective	638
	Refe	erences		639
				641
23	Wha	at is fati	gue damage? A viewpoint from the observation	
	or a	row-cyc	ie langue process	643
	23.1			643
	23.2		e damage in low-cycle fatigue and the behaviour	
		23.2.1	Material and test procedure	644
		23.2.2	Experimental results and discussion	644
	23.3	Ductili	ity loss during the fatigue process	645
		23.3.1	Effects of small surface cracks on ductility	657
			loss during low-cycle fatigue	
		23.3.2	Material and test procedure	657
		23.3.3	Results and discussion	658
	23.4	Experi	mental conclusions	660
	23.5	_	ary in terms of the second of	666
	-0.0		ary in terms of the correlation among fatigue damage,	
	Refer	ences	racks, Coffin—Manson law and ductility loss	666
	210101	Oncos		667
4	Quali analy	ty contr	ol of mass production components based on defect	
	24.1	Introdu		669
	24.2			669
	24.2	The im	portance of prediction of the extreme value	
	24.3	baseu o	if the statistics of extremes	670
	24.5	Preyent	ion method for recalls	673
		24.3.1	How to find the cause of failure and the	0.0
		0400	method of statistics extremes analysis	673
	•	24.3.2	Statistics of extremes data of defects as failure	075
			cause and its applications to fatigue design	674
		24.3.3	Practical applications to design and quality	07-4
	24.4		control based on the statistics of extremes	675
	24.4	Basic co	incept and guide for the application of the	075
		stausucs	or extremes method	682
		24.4.1	What is the appropriate parameter?	682
		24.4.2	Reconsideration of the stress—strength model	682
	2	24.4.3	Applications to large-scale but a small number	082
			of production machinery	600
		Conclusi	ons	683
	Referer			684
	Append	lix: Defi	nition of the control volume as the potential risk	684
	volume	under h	igh applied stress	606
			· -	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

xv