Cambridge University Press 0521781256 - The Theory of Composites Graeme W. Milton Table of Contents More information

Contents

	List of figures	xix
	Preface 22 References 23	xxiii xxvi
1	Introduction	1
1.1	What are composites, and why study them?	1
1.2	What makes composites useful?	2
1.3	The effective tensors of composites	5
1.4	Homogenization from an intuitive viewpoint	7
1.5	Periodic homogenization	8
1.6	Homogenization in random media	11
1.7	Homogenization in the settings of G -, H -, and Γ -convergence	12
	References	14
2	Some equations of interest and numerical approaches to solving them	19
2.1	The conductivity and related equations	19
2.2	Magnetotransport and convection enhanced diffusion	21
2.3	The elasticity equations	22
2.4	Thermoelectric, piezoelectric, and similar coupled equations	28
2.5	Thermoelasticity and poroelasticity	30
2.6	Pyroelectric equations and their relation to conductivity and magnetotrans- port equations in fibrous composites	33
2.7	The equivalence between elasticity in fibrous composites and two-dimensional piezoelectricity and thermoelasticity	35
2.8	Numerical methods for finding effective tensors References	38 40

Sections or chapters marked with a dagger (\dagger) can be skipped on a first reading of the book. They contain material that is not central to the book, or they include more advanced or more technical subject matter. However, they also sometimes address topics that are at the forefront of current research.

CAMBRIDGE

X	Contents	
3	Duality transformations in two-dimensional media	47
3.1	Duality transformations for conductivity	47
3.2	Phase interchange identities for two-phase media	49
3.3	The conductivity of two-dimensional polycrystals	50
3.4	Duality transformations for pyroelectricity	51
3.5	Duality transformations for elasticity	51
3.6	Duality transformations for other elastic media	53
3.7	The effective shear modulus of incompressible two-dimensional polycrys-	
	tals and symmetric materials	55
	References	57
4	Translations and equivalent media	59
4.1	Translations applied to conductivity	59
4.2	A formula for the Hall coefficient in two-dimensional polycrystals	60
4.3	A formula for the Hall coefficient in two-phase, two-dimensional media [†]	61
4.4	Inhomogeneous translations for three-dimensional conductivity	65
4.5	Translations for elasticity	66
4.6	A proof that the Young's modulus of a metal plate with holes does not	
	depend on the Poisson's ratio of the metal	67
4.7	The elastic moduli of certain two-dimensional polycrystals and symmetric	
	materials	69
	References	70
5	Some microstructure-independent exact relations	75
5.1	The uniform field argument	75
5.2	The bulk modulus of polycrystals with cubic symmetry	76
5.3	The elastic moduli of a composite with a constant shear modulus	77
5.4	The thermal expansion tensor and constant of specific heat in a composite	
	of two isotropic phases	79
5.5	The extension to nonlinear thermal expansion	81
5.6	The thermal expansion tensor and specific heat in composites of two	
	anisotropic phases	82
5.7	Exact thermoelastic relations for polycrystals	83
5.8	The effective poroelastic moduli of two-phase media	84
5.9	The elastic moduli of two-phase fibrous composites	86
5.10	Exact relations for pyroelectric, conductivity, and magnetotransport equations	87
5.11	The bulk modulus of a suspension of elastic particles in a fluid	88
	References	89
6	Exact relations for coupled equations	93
6.1	The covariance property of the effective tensor	93
6.2	The reduction to uncoupled equations for two-phase composites with	a -
	isotropic phases	95
6.3	Translations for coupled equations	97
6.4	Elasticity as a special case of coupled field equations	98
6.5	Equivalent coupled field problems in two dimensions	101

Contents

xi

6.6	The two-dimensional equations as a system of first-order partial differential	100
	equations	103
6.7	The covariance property of the fundamental matrix	104
0.8	Linking special classes of antiplane and planar elasticity problems	105
6.9	Expressing the fields in each phase in terms of analytic functions	106
	Keterences	110
7	Assemblages of spheres, ellipsoids, and other neutral inclusions	113
7.1	The coated sphere assemblage	113
7.2	Multicoated sphere assemblages	117
7.3	A phase interchange identity and inequality	118
7.4	Assemblages of spheres with varying radial and tangential conductivity	120
7.5	The conductivity of Schulgasser's sphere assemblage	121
7.6	The conductivity of an assemblage of spheres with an isotropic core and	
	polycrystalline coating	123
7.7	Assemblages of ellipsoids and their associated Ricatti equations [†]	124
7.8	The conductivity of an assemblage of coated ellipsoids [†]	127
7.9	A solution of the elasticity equations in the coated ellipsoid assemblage	130
7.10	Expressions for the depolarization factors [†]	132
/.11	Neutral coated inclusions	134
	Keterences	139
8	Tricks for generating other exactly solvable microgeometries	143
8.1	Modifying the material moduli so the field is not disturbed	143
8.2	Assemblages of coated spheres and coated ellipsoids with anisotropic cores	144
8.3	Making an affine coordinate transformation	145
8.4	The conductivity of an assemblage of coated ellipsoids with an anisotropic	
	core and coating	148
8.5	Making a curvilinear coordinate transformation [†]	149
8.6	Quasiconformal mappings	152
8.7	Generating microgeometries from fields	153
	References	155
9	Laminate materials	159
9.1	The history of laminates and why they are important	159
9.2	Elementary lamination formulas	159
9.3	Lamination formulas when the direction of lamination is arbitrary	164
9.4	Tartar's lamination formula for two-phase simple and coated laminates	165
9.5	Lamination formulas for elasticity, thermoelasticity, thermoelectricity, and	
	piezoelectricity	167
9.6	The lamination formula for a coated laminate with anisotropic coating and	171
07	anisotropic core	1/1
9./	Kelerence transformations	172
9.8	Explicit formulas for the conductivity and elasticity tensors of a coated	172
0.0	Iammaic Ordinary differential laminates [†]	175
7.7 0.10	Dortial differential laminates	173
9.10	r attat utitetetittät tättillätes	1//
	KUUUUUU	101

CAMBRIDGE

xii	Contents	
10	Approximations and asymptotic formulas	185
10.1	Polarizability of a dielectric inclusion	185
10.2	Dielectric constant of a dilute suspension of inclusions to the first order in the volume fraction	188
10.3	Dielectric constant of a suspension of well-separated spheres to the second order in the volume fraction	189
10.4	The Maxwell approximation formula	192
10.5	The effective medium approximation for the dielectric constant of an aggregate with spherical grains	195
10.6	Average field approximations [†]	198
10.7	The differential scheme for the effective conductivity of a suspension of spheres	201
10.8	The effective medium approximation as the attractor of a differential scheme	203
10.9	Approximation formulas for effective elastic moduli	204
10.10	Asymptotic approximation formulas	207
10.11	Critical exponents and universality	211
	References	213
11	Wave propagation in the quasistatic limit	221
11.1	Electromagnetic wave propagation in the quasistatic limit	222
11.2	Electromagnetic signals can propagate faster in a composite than in the constituent phases	228
11.3	Elastic wave propagation in the quasistatic limit	230
11.4	The correspondence principle and the attenuation of sound in a bubbly fluid	233
11.5	Transformation to real equations	234
11.6	Correspondence with thermoelectricity in two dimensions	237
11.7	Resonance and localized resonance in composites [†]	238
	References	242
12	Reformulating the problem of finding effective tensors	245
12.1 12.2	Resolving a periodic field into its three component fields: The Γ -operators A wider class of partial differential equations with associated effective	245
	tensors†	248
12.3	A related Γ-operator	250
12.4	The equation satisfied by the polarization field	251
12.5	The effective tensor of dilute suspensions of aligned ellipsoids	252
12.6	Expressions for the action of the Γ -operators in real space	257
12.7	A framework for defining effective tensors in a more general context	260
12.8	Various solutions for the fields and effective tensor	261
12.9	The duality principle	262
12.10	The effective tensor of the adjoint equation	263
12.11	Magnetotransport and its equivalence to thermoelectricity in two dimensions	264
	References	267

	Contents	xiii
13	Variational principles and inequalities	271
13.1	Classical variational principles and inequalities	271
13.2	Monotonicity of the effective tensor	274
13.3	Null Lagrangians	274
13.4	Variational principles for problems with a complex or other non-self-adjoint	
	tensor	276
13.5	Hashin-Shtrikman variational principles and inequalities	278
13.6	Relation between the Hashin-Shtrikman and classical variational inequalities [†]	281
13.7	Variational inequalities for nonlinear media	282
	References	286
14	Series expansions for the fields and effective tensors	291
14.1	Expanding the formulas for the effective tensors and fields in power series	291
14.2	The series expansion in a composite to second order	292
14.3	Thermoelastic composites for which the third and higher order terms in the	
	expansion vanish	294
14.4	A large class of exactly solvable materials with complex moduli	295
14.5	Reducing the dimensionality of the problem [†]	297
14.6	Convergence of the expansions and the existence and uniqueness of the	200
147	Convergence when <i>L</i> is not self adjoint [†]	298 300
14.7	Extending the domain of convergence ^{\pm}	300
14.0	A series with a faster convergence rate	302
14.10	A related series that converges quickly	304
14.11	Numerical computation of the fields and effective tensor using series	201
	expansions	306
	References	309
15	Correlation functions and how they enter series expansions [†]	313
15.1	Expressing the third-order term of the series expansion in terms of correla-	
150	tion functions	313
15.2	The terms in the series expansion for random media	315
15.3	Correlation functions for penetrable spheres	319
15.4	Correlation functions for cell materials	320
15.5	Expansions for two phase rendom composites with geometric isotropy	323 327
15.0	Series expansions for cell materials with geometric isotropy	327
15.7	References	335
	Keleicies	555
16	Other perturbation solutions	341
16.1	Effect of a small variation in the material moduli	341
16.2	Application to weakly coupled equations of thermoelectricity or piezoelec-	317
163	Application to computing the effective Hall coefficient	342 344
16.5	The variance of the electric field in a two-phase conducting composite	344
16.5	Bounds on the conductivity tensor of a composite of two isotronic phases	346
16.6	The change in the effective tensor due to a shift in the phase boundary [†]	347

xiv	Contents	
16.7	Perturbing the lamination directions in a multiple-rank laminate [†] References	351 352
17	The general theory of exact relations and links between effective tensors	355
17.1	Links between effective tensors as exact relations: The idea of embedding	355
17.2	Necessary conditions for an exact relation	357
17.3	Sufficient conditions for an exact relation	359
17.4	nolvervstals	361
17.5	More exact relations for coupled equations [†]	362
17.6	Exact relations with limited statistical information	363
17.7	Additional necessary conditions for an exact relation [†]	365
	References	367
18	Analytic properties	369
18.1	Analyticity of the effective dielectric constant of two-phase media	369
18.2 18.3	Analyticity of the effective tensor for problems involving many eigenvalues Integral representations for the effective tensor for problems involving two	370
10 /	eigenvalues	3/3
18.4	The correspondence between effective conductivity functions and microge-	301
10.5	ometries in two dimensions [†]	383
18.6	Integral representations for problems involving more than two eigenvalues:	
	The trajectory method	387
18.7	The lack of uniqueness in the choice of integral kernel: Constraints on the	
	measure†	389
18.8	Integral representations for a broader class of composite problems [†]	391
	Keterences	391
19	Y-tensors	397
19.1	The <i>Y</i> -tensor in two-phase composites	397
19.2	The Y-tensor in multiphase composites	399
19.5	V tensor	403
194	The Hilbert space setting for the Y-tensor problem ⁺	405
19.5	The Y-tensor polarization problem [†]	408
19.6	Variational inequalities and principles for Y-tensors [†]	409
	References	411
20	Y-tensors and effective tensors in electrical circuits [†]	413
20.1	The incidence matrix and the fields of potential drops and currents	413
20.2	The subdivision of bonds in an electrical circuit	415
20.3	The <i>Y</i> -tensor of the electrical circuit	417
20.4	The effective tensor of the passive network $T_{\rm eff}$	418
20.5	The interpretation of the subspace $\mathcal{U}^{(1)}$	419
20.0	circuit	421
	References	423

CAMBRIDGE

	Contents	XV
21	Bounds on the properties of composites	425
21.1	Why are bounds useful?	425
21.2	What are bounds?	426
21.3	The role of bounds in structural optimization: A model problem	429
	References	433
22	Classical variational principle bounds	437
22.1	Multiphase conducting composites attaining energy bounds	437
22.2	Optimal bounds on the conductivity of isotropic polycrystals	439
22.3	Optimal bounds on the bulk modulus of isotropic polycrystals	441
22.4	The complete characterization of the set $G_f U e_0$ for <i>n</i> -phase composites and polycrystals	444
22.5	The <i>G</i> -closure in two dimensions of an arbitrary set of conducting materials	446
22.6	Bounds on complex effective tensors [†]	450
	References	452
23	Bounds from the Hashin-Shtrikman variational inequalities	457
23.1	Bounds on the effective conductivity of an isotropic composite of <i>n</i>	
	isotropic phases	457
23.2	Optimal bounds on the effective conductivity of an anisotropic composite	
	of two isotropic phases	461
23.3	Bounds for two-phase, well-ordered materials	462
23.4	Bounds on the energy that involve only the volume fractions	465
23.5	Bounds on the effective tensor that involve only the volume fractions	468
23.6	Bounds for two-phase composites with non-well-ordered tensors [†]	474
23.7	Bounding the complex effective moduli of an isotropic composite of two	
	isotropic phases [†]	476
23.8	Using quasiconformal mappings to obtain bounds	480
23.9	Optimal two-dimensional microgeometries: Reduction to a Dirichlet	
	problem†	481
23.10	Bounds for cell polycrystals	487
	References	490
24	Bounds using the compensated compactness or translation method	499
24.1	The translation bound and comparison bound	499
24.2	Upper bounds on the bulk modulus of two-phase composites and polycrys- tals in two dimensions	500
24.3	Allowing quasiconvex translations	503
24.4	A lower bound on the effective bulk modulus of a three-dimensional, two-	
	phase composite	504
24.5	Using the idea of embedding to extend the translation method	505
24.6	Bounds on the conductivity tensor of a composite of two isotropic phases	506
24.7	The translation bounds as a corollary of the comparison bounds [†]	509
24.8	Embedding in a higher order tensorial problem: A lower bound on the	
	conductivity tensor of a polycrystal	510
24.9	A geometric characterization of translations [†]	512
24.10	Translation bounds on the Y-tensor	516

xvi	Contents	
24.11 24.12	Deriving the trace bounds [†] Mixed bounds	518 519
24.13	Volume fraction independent bounds on the conductivity of a mixture of two isotropic phases	520
24.14	Bounds correlating different effective tensors References	522 525
25	Choosing the translations and finding microgeometries that attain the	
	bounds†	529
25.1	Other derivations of the translation bounds and their extension to nonlinear problems	529
25.2	Extremal translations	532
25.3	Attainability criteria for the comparison bounds	535
25.4	Isotropic polycrystals with minimum conductivity constructed from a fully anisotropic crystal	537
25.5	Attainability criteria for the translation bounds	541
25.6	Attainability criteria for the Hashin-Shtrikman-Hill bounds on the conduc- tivity and bulk modulus	542
25.7	A general procedure for finding translations that generate optimal bounds	
	on sums of energies	544
25.8	Translations for three-dimensional elasticity References	547 550
26	Bounds incorporating three-point correlation functions [†]	553
26.1	A brief history of bounds incorporating correlation functions	553
26.2	Three-point bounds on the conductivity of a two-phase mixture	554
26.3	Three-point bounds on the elastic moduli of a two-phase mixture	557
26.4	Correlation function independent elasticity bounds: Improving the Hashin-	~~~
26.5	Shtrikman-Hill-Walpole bounds	558
26.5	Using the translation method to improve the third-order bounds	560
20.0 26.7	Ceneral third order bounds for a two phase composite	562
20.7	Third order bounds for two phase composites with geometrical isotropy	564
20.8	References	564
27	Bounds using the analytic method	569
27.1	A brief history of bounds derived using the analytic method	569
27.2	A topological classification of rational conductivity functions	571
27.3	Bounds that incorporate a sequence of series expansion coefficients	5/3
27.4	Relation between the bounds and Pade approximants	5/8
21.3	bounds incorporating known real or complex values of the function and series expansion coefficients	570
27.6	Numerical computation of the bounds ⁺	583
27.0	Bounds for two-dimensional isotropic composites [†]	585
27.8	Bounds for symmetric materials [†]	588
27.9	Reducing the set of independent bounds	589

	Contents	xvii
27.10 27.11	Proving elementary bounds using the method of variation of poles and residues Proving the bounds using the method of variation of poles and zeros	590 592
	References	596
28	Fractional linear transformations as a tool for generating bounds [†]	603
28.1	Eliminating the constraints imposed by known series expansion coefficients	603
28.2 28.3 28.4	An alternative approach that treats the components on a symmetric basis The extension of the fractional linear transformations to matrix-valued	610
	analytic functions	614
	References	617
29	The field equation recursion method [†]	619
29.1	subspace collections	619
29.2	Hints of a deeper connection between analytic functions and subspace	017
	collections	624
29.3	The field equation recursion method for two-phase composites	626
29.4 29.5	Representing the operators as infinite-dimensional matrices The field equation recursion method for multiphase composites with	631
29.6	Bounds on the energy function of a three-phase conducting composite	033 638
27.0	References	641
30	Properties of the G-closure and extremal families of composites	643
30.1	An equivalence between G-closure problems with and without prescribed	(10)
30.2	volume fractions Stability under lamination and the convexity properties of the <i>C</i> closure	643 645
30.2 30.3	Characterizing the <i>G</i> -closure through minimums of sums of energies and complementary energies	647
30.4	Characterization of the <i>G</i> -closure by single energy minimizations	650
30.5	Extremal families of composites for elasticity: Proving that any positive- definite tensor can be realized as the effective elasticity tensor of a	000
	composite†	652
30.6	An extremal family of unimode materials for two-dimensional elasticity [†]	658
30.7	An extremal family of bimode materials for two-dimensional elasticity	663
30.8	Extremal materials for three-dimensional elasticity References	000 667
		007
31	The bounding of effective moduli as a quasiconvexification problem	671
31.1 31.2	Quasiconvexification problems in elasticity theory The independence of the quasiconvexified function on the shape and size of	671
31.3	the region Ω Replacing the affine boundary conditions with periodic boundary conditions	674 675

xviii	Contents	
31.4	The equivalence of bounding the energy of multiphase linear composites	
	and quasiconvexification	677
31.5	The link between the lamination closure and A-convexification	679
31.6	Quasiconvex hulls and rank-1 convex hulls	681
31.7	Laminate fields built from rank-1 incompatible matrices	683
31.8	Example of a rank-1 function that is not quasiconvex [†]	684
31.9	A composite with an elasticity tensor that cannot be mimicked by a	
	multiple-rank laminate material [†]	690
	References	695
	Author index	699
	Subject index	711