AP42 Section:	10.5
Reference:	3
Title:	T. Baumeister, ed., Plywood, *Standard Handbook For Mechanical Engineers*, Seventh Edition, McGraw-Hill, New York, NY, 1967, pp. 6-162 - 6-169. 2002 supplement

Table 5. Allowable Unit Stresses for Machine-Stress-Rated Lumber (From National Design Specification) (*Continued*)

Grading rules agency, grade designation	Size classification	Allowable unit stresses, lb/in²								
		Extreme fiber in bending F_b*		Tension parallel to grain F_t	Compression parallel to grain F_c	Compression perpendicular to grain $F_{c\perp}$ (dry)†				Modulus of elasticity E
		Single-member uses	Repetitive-member uses			Douglas fir-larch	Hem-fir	Pine‡	Engelmann spruce	Cedar§	
Southern Pine Inspection Bureau										
						Southern pine					
1,200f-1.2E		1,200	1,375	600	950	405					1,200,000
1,500f-1.4E	Machine-rated lumber 2 in thick or less, 2–4 in wide	1,500	1,725	900	1,200	405					1,400,000
1,650f-1.5E		1,650	1,900	1,020	1,320	405					1,500,000
1,800f-1.6E		1,800	2,100	1,175	1,450	405					1,600,000
2,100f-1.8E		2,100	2,400	1,575	1,700	405					1,800,000
2,400f-2.0E		2,400	2,750	1,925	1,925	405					2,000,000
2,700f-2.2E		2,700	3,100	2,150	2,150	405					2,200,000
3,000f-2.4E		3,000	3,450	2,400	2,400	405					2,400,000
3,300f-2.6E		3,300	3,800	2,650	2,650	405					2,600,000
900f-1.0E	Machine-rated lumber 2 in thick or less, 6 in and wider	900	1,025	350	725	405					1,000,000
900f-1.2E		900	1,025	350	725	405					1,200,000
1,200f-1.5E		1,200	1,375	600	950	405					1,500,000
1,350f-1.8E		1,350	1,550	750	1,075	405					1,800,000
1,800f-2.1E		1,800	2,050	1,175	1,450	405					2,100,000

*Tabulated extreme fiber in sending values F_b are applicable to lumber loaded on edge. When loaded flatwise, these values should be multiplied by the following factors:

Nominal width, in	4	6	8	10	12	14
Factor	1.10	1.15	1.19	1.22	1.25	1.28

Douglas fir-larch	Hem-fir	Pine	Engelmann spruce	Cedar	Southern pine
95	75	65	70	75	90
			For southern pine KD		95

†Allowable unit stresses for horizontal shear F_v (dry) for all grade designations are as follows:

Douglas fir-larch	Hem-fir	Pine‡	Engelmann spruce	Cedar§	Southern pine
95	75	65	70	75	90
			For southern pine KD		95

‡Pine includes Idaho white, lodgepole, ponderosa, or sugar pine.
§Cedar includes incense or western red cedar.

Table 6. Allowable Unit Stresses for Plywood (Douglas Fir and Western Larch)
(For grades and thicknesses listed in USCS45–60) (Values given are for permanent loads; for normal load-year loading, increase by 10 percent.)

Type of stress	Dry Location					Wet or Damp Location				
	Ext A-A	Ext A-B Ext A-C	Ext concrete form B-B Ext B-C Ext C-C Int concrete form B-B Int sheathing C-D Int sheathing C-D (ext glue)	All other grades conforming to USCS45-60, with Coast Douglas fir faces and backs and with inner plies of Douglas fir or any Western softwood species listed in Groups 1, 2, or 3 of USCS122-60 (apply the following percentages to stresses for corresponding Ext grade)	Ext A-A	Ext A-B Ext A-C	Ext concrete form B-B Ext B-C Ext C-C Int concrete form B-B Int sheathing C-D Int sheathing C-D (ext glue)	All other grades conforming to USCS45-60, with Coast Douglas fir faces and backs and with inner plies of Douglas fir or any Western softwood species listed in Groups 1, 2, or 3 of USCS122-60 (apply the following percentages to stresses for corresponding Ext grade)
Extreme fiber in bending								
Face grain // to span	2,188	2,000	1,875	100 %	1,094	1,000	938	100 %
Face grain ⊥ to span	1,875	1,875	1,875	85 %	938	938	938	85 %
Tension								
// to face grain (3 ply only*)	2,188	2,188	1,875	100 %†	1,094	1,094	938	100 %†
⊥ to face grain	1,875	1,875	1,875	65 %	938	938	938	65 %
± 45° to face grain	337	320	310	75 %	169	160	155	75 %
Compression								
// to face grain (3 ply only*)	1,605	1,460	1,375	100 %‡	1,605	1,460	1,375	100 %‡
⊥ to face grain	1,375	1,375	1,375	60 %	1,375	1,375	1,375	60 %
± 45° to face grain	496	472	460	70 %	496	472	460	70 %
Bearing (on face)	405	405	405	100 %	405	405	405	100 %
Shear, rolling, in plane of plies†								
// or ⊥ to face grain	79	72	68	75 %	39	36	34	75 %
± 45°	105	96	90	75 %	52	48	45	75 %
Shear in plane ⊥ to plies								
// or ⊥ to face grain	260	240	225	80 %	130	120	113	80 %
± 45°	520	480	450	80 %	260	240	225	80 %
Modulus of elasticity in bending								
Face grain // to span	1,600,000	1,600,000	1,600,000	100 %	1,600,000	1,600,000	1,600,000	100 %
Face grain ⊥ to span	1,600,000	1,600,000	1,600,000	60 %	1,600,000	1,600,000	1,600,000	60 %

*For tension or compression, // to grain, in 3 ply or thicker, use values for 5 ply, but in next lower grade.
†For the flange-web joints of beams having plywood webs and for joints between the skin and framing members located at the edges of stressed-skin plywood panels, these values shall be reduced by 50 percent.
‡For 5 or more plies, use 80 percent.
Example: The working stress in compression // for A-D 5-ply (1,100 lb/in²) is found by multiplying the value for Exterior (C-C) 3-ply, 1,375 lb/in², by 80 %, the reduction factor shown in the last column and footnote * and ‡.
Where moisture content will exceed 16 %, decrease by 20 % values shown for dry location for following properties:
Extreme fiber in bending, tension, and compression both // and ⊥ to the grain and at 45°, and bearing. (No change in values for rolling shear or modulus of elasticity.)

PLYWOOD

Plywood is the name given to a wood panel glued under pressure from an odd number of layers or plies of veneer or veneer and lumber, in which alternate plies are laid with the grain at right angles. The alternation of grain direction in adjacent plies equalizes the sheet in the two face directions in strength, stiffness, and dimensional changes.

Balanced construction in plywood results in minimum warpage in the sheet. Balance is determined by considering veneer thicknesses, shrinkage, elasticity, moisture content, and grain angle as factors in the moments of pairs of plies about the neutral axis of the sheet. Balance is especially critical in thin sheets.

The two outside veneer sheets in a plywood panel are known as the **faces** or **face and back**. The interior ply or plies whose grain direction parallels the face is a **core**, if single, or **centers**, if more than one is used. The interior plies whose grain is perpendicular to that in the faces are the **cross bands**. Plywood stock sheets range from three to seven plies and ⅛ to 1⅛ in thick and are usually 4 by 8 ft in surface. Special smaller sizes are produced to order, particularly in hardwoods. Lengths up to 30 ft can be made at the mills, by splicing. Commercial thicknesses and ply construction of Douglas fir plywood are shown in Table 7.

Plywood can be made of veneers cut from any kind of wood; however, technical difficulties of glue compatibility and veneer cutting restrict production plywood to a few kinds of wood. Depending on the botanical identity of the wood in the sheets, plywood is classed as hardwood or softwood. For both classes the sheets are made in two types that reflect the moisture resistance of the glue joints. Douglas fir plywood, which is the principal construction plywood in the United States, is made as (1) **interior**, a type that will maintain its shape and most of its strength when occasionally subjected to a thorough wetting and subsequent normal drying; and (2) **exterior**, a type of plywood which must retain its shape and strength when repeatedly wet and dried under adverse conditions and be suitable for permanent outdoor exposure. The

latter is also called **marine plywood.** Interior plywood is usually bonded with soybean glue or an extended resin adhesive, while exterior panels are made with hot-pressed phenol resins. The **grade of plywood** is based on the quality of the veneers on the faces of the sheet. Veneer grades for Douglas fir and most other western softwoods are A, B, C, and D, in decreasing order of quality. Hardwood veneers are graded as 1, 2, 3, 4, with number 1 as highest quality. The **grade designation** of plywood will include the type and the veneer grades, as, for example, Ext-DFPA-Plyshield-(A-C), in which the face is grade A and the back C. The inner plies of commercial Douglas fir panels are made up with grade C for exterior type and grade D for the interior-type plywood. The various grades of Douglas fir plywood are shown in Table 6.

Strength of Plywood

The allowable stress values for solid wood cannot be transposed directly to plywood because of the alternation of ply directions and the fact that knots and other major defects are confined to single plies. Precise equations for strength, based on the composite section and involving all plies, are given in Design of Wood Aircraft Structures, *ANC Bull.* 18. These calculations are involved and yield too refined answers for most applications.

Recommended Working Stresses for Douglas Fir Plywood

Approximate methods for the calculation of plywood strength have been developed and tested by the USFPL (R-1630, Apr. 1956). These methods are suitable for estimating the strength and stiffness of plywood and are sufficiently accurate for general design use, provided that the plywood is not stressed to buckling. Working stresses based on this system for various grades of Douglas fir are shown in Table 6. These stresses should be used only with the restrictions in the following paragraphs.

Tension and compression approximations take into account only those plies with grain parallel to load direction. Consequently, the choice of stress in the table must be made on basis of face-grain direction with respect to load direction. The values for parallel (∥) to face grain, perpendicular (⊥) to face grain, and 3 ply as against 5 or more plies differ because the inner plies are poorer grade veneer which carry lower stresses. Stress direction at 45° to face grain requires the full cross-sectional area to be used in computations because none of the plies in the sheet are parallel to the load direction. Calculations will be simplified for standard plywood constructions by the use of the section properties given in Table 7.

Bending load for plywood, based on *Bull.* 1630, is calculated by a modified flexure formula $M = KSI/c$, in which M is the bending moment; S is the unit stress for extreme fiber in bending of those plies in the parallel-to-span direction; I is the moment of inertia computed on basis of plies parallel to span only; c is the distance from neutral axis to outermost fiber of the outermost ply having its grain in the direction of the span; $K = 1.50$ for 3-ply plywood having the grain of the outer plies perpendicular to the span; $K = 0.85$ for all other plywood.

Deflection in bending is approximated by the usual equations, except that the moment of inertia I is a composite term made up of the sum of the moments of inertia for the plies parallel to span, plus one-twentieth that of the plies perpendicular to span. For thin sheets of plywood (¼ in and under), the perpendicular plies contribute less than 10 percent to the total and may be neglected in calculations. However, as sheet thickness increases, the I perpendicular approaches the value of I parallel, and must be included.

Shear in plywood is of two types. The stress listed in Table 6 as shear in plane perpendicular (⊥) to plies is that developed in the plywood web of a built-up I, or box beam. The second kind of shear is set up in the plane of the plies as normal horizontal shear in a beam. Because the cells of the wood in a direction normal to their length are deformed at low stress levels, the shear is limited in this case by the plies perpendicular to stress direction. Such shear action is called **rolling shear** in plywood. Stress concentrations as exist between flanges and webs of I and box beams and framing members at edges of panels should be computed using 50 percent of tabulated rolling-shear stress.

Shrinkage in Plywood

The range of possibilities in kinds of wood, combinations within a sheet, thickness, and numbers of plies makes the tabulation of shrinkage data impossibly cumbersome. Calculations can be made using the methods given by C. B. Norris in "Techniques of Plywood." Studies have been made by the U.S. Forest Products Laboratory for 3-ply panels of one kind of wood, and of equal ply thicknesses, dried from soaked to ovendry condition, and ranging in thickness from 1/10 to ⅛ in. Shrinkage in such panels averages 0.45 percent parallel to the face grain and 0.67 percent perpendicular to the face grain, and varies from 0.2 to 1 percent and 0.3 to 1.2 percent, respectively.

PRESERVATIVE TREATMENT OF WOOD

Since few woods are resistant to deterioration under adverse conditions, and the sterilization provided by steam treating and kiln drying is not permanent, the principal method for protection of wood in service is the introduction of toxic chemicals into the wood.

Materials for Protection against Biological Action

Oils and oil-borne preservatives are the chief materials in use today. **Coal-tar creosote,** which is the most widely used, is a by-product distilled from the coal tar produced by high-temperature carbonization of bituminous coal. It consists of a heterogeneous mixture of liquid and solid hydrocarbons having a continuous boiling range from about 200 to 325°C. Analysis methods, as given by the American Wood Preservers Assoc., are important since the chemical composition and related toxicity of coal-tar creosote is variable. The fraction distilling in the 200 to 275°C range appears to be the most toxic. As a means of reducing cost or increasing penetration, **creosote-coal tar solutions** and **creosote-petroleum solutions** have been used extensively. Such solutions are used in proportions as high as 50 percent. Toxicity of the petroleum solutions is reduced in a ratio greater than indicated by the percentage of diluent added. **Pentachlorophenol** in volatile petroleum carries is nearly as important a preservative as creosote and is favored where cleanliness and paintability are necessary. Usual concentrations of pentachlorophenol for wood treatment are not less than 5 percent by weight. This produces a solution in the same range of cost as coal-tar creosote and can be used in roughly the same range of retentions as the latter.

Table 7. Moments of Inertia, Section Moduli, and Veneer Areas for Selected Plywood Constructions (12-in widths)
(From "Technical Data on Plywood," Douglas Fir Plywood Assoc.)

Net plywood thickness	No. of plies	Veneer thickness (nominal), in.			Parallel‡ plies only			Perpendicular‡ plies only		
		Faces§	Centers	Crossband	Area, sq. in.	Moment of inertia I, in⁴	Section modulus S, in³	Area, sq. in	Moment of inertia I, in⁴	Section modulus S, in³
¼"—S†	3	1/16	1/16	.....	0.75	0.0017	0.027	0.75	0.0002	0.0077
5/16"—S	3	1/12	1/12	.....	1.25	0.0060	0.064	1.00	0.0006	0.0139
¼"—R*	3	1/12	1/12	.....	2.00	0.0150	0.120	1.00	0.0006	0.0139
7/16"—S	3	1/8	1/8	.....	1.67	0.0143	0.114	1.33	0.0014	0.0247
5/16"—R	3	1/10+	1/10+	.....	2.50	0.0294	0.188	1.25	0.0011	0.0215
5/16"—S	3	1/8	1/8	.....	2.25	0.0286	0.183	1.50	0.0020	0.0312
3/8"—R	3	1/8	1/8	.....	3.00	0.0509	0.271	1.50	0.0020	0.0312
3/8"—S	3	1/8	3/16	.....	2.25	0.0461	0.246	2.25	0.0066	0.0704
3/8"—S	5	1/10	1/12	2@1/12	2.50	0.0377	0.201	2.00	0.0150	0.120
7/16"—S	5	1/10	1/10	2@1/10	2.85	0.0575	0.263	2.40	0.0260	0.1735
7/16"—R	5	1/10	1/10	2@1/10	3.60	0.0990	0.396	2.40	0.0260	0.1735
7/16"—S	5	1/8	1/8	2@1/10	3.60	0.0926	0.370	2.40	0.0324	0.1995
15/32"—S	5	1/8	1/8	2@1/8	3.75	0.1273	0.452	3.00	0.0507	0.271
15/32"—R	5	1/8	1/8	2@1/8	4.50	0.1934	0.619	3.00	0.0507	0.271
15/32"—S	5	1/8	3/16	2@1/8	4.50	0.1670	0.534	3.00	0.0771	0.352
1 1/16"—S	5	1/8	1/8	2@3/16	3.75	0.202	0.588	4.50	0.123	0.492
1/2"—R	5	1/8	1/8	2@3/16	4.50	0.299	0.798	4.50	0.123	0.492
1/2"—S	5	1/8	3/16	2@3/16	4.50	0.251	0.670	4.50	0.171	0.608
1/2"—S	7	1/8	2@1/12	3@1/8	4.50	0.286	0.763	4.50	0.136	0.503
1 3/16"—S	7	1/8	2@1/8	3@1/8	5.25	0.343	0.845	4.50	0.193	0.617
19/32"—S	7	1/8	2@3/32	3@1/8	6.00	0.427	0.976	4.50	0.243	0.707
1 5/16"—S	7	1/8	2@3/16	3@1/8	6.75	0.525	1.120	4.50	0.299	0.797
1"—S	7	1/8	2@1/8	3@3/16	5.25	0.540	1.080	6.75	0.460	1.131
1 1/16"—S	7	1/8	2@1/8	3@3/16	6.00	0.615	1.157	6.75	0.585	1.305
1 1/32"—R¶	7	1/10	2@3/16	3@3/16	6.90	0.798	1.419	6.66	0.627	1.115
1 1/16"—S	7	1/8	2@3/16	3@3/16	6.75	0.771	1.371	6.75	0.653	1.395
1 3/16"—S	7	1/8	2@3/32	3@3/16	7.50	0.912	1.538	6.75	0.763	1.526

*Rough.
†Sanded.
‡Refers to direction of face grain.
§For sanded panels, thickness is before sanding.
¶Interior floor panel 2-4-1 grade.

Water-borne solutions of inorganic salts have advantages over the oils in greater ease of penetration and freedom from fire hazards and odor; however, they do cause swelling and some react with metal. The principal preservative of this class is chromated zinc chloride. Some other salts used are: acid cupric chromate (Celcure), ammoniacal copper arsenate (Chemonite), chromated copper arsenate (Green salt or Erdalith), chromated zinc arsenate (Boliden salt), copperized chromated zinc chloride. Retention for salts used in wood preserving is stated in pounds of dry salt per cubic foot of material.

Preparation of Material

Wood which is to be pressure-treated must be peeled to hasten drying and permit maximum preservative absorption. Barking can be done by hand shaving or in a peeling machine which smoothes and straightens the poles. Machine peeling results in lower pole strengths and less penetration for many kinds of wood.

Seasoning ordinarily is done by air drying to about 15 percent moisture content. When green material must be used for treating, two seasoning methods are common. **Steam conditioning** is usually used with southern pine. The wood in the treating cylinder is steamed for several hours at about 30 lb/in², following which a vacuum is drawn on the charge for several hours. MacLean (*U.S. Dept. Agr. Misc. Publ.* 224, rev. 1953) has worked out charts showing cycles required and temperatures attained for various sizes of material. **Boiling under vacuum** (Boulton process) is extensively used for Douglas fir and red oak. The charge in a cylinder is submerged in hot oil, and a vacuum drawn so that the water boils out of the wood.

Adzing, boring, framing, and all other cutting should be completed prior to treatment, since this will ensure all surfaces are adequately penetrated.

Incising is a process by which chisel-pointed teeth are forced into the side grain of the wood to about half-inch depths. Primary purpose is to expose more end grain and give greater penetration in woods such as western red cedar and Douglas fir.

Methods for Preservative Treatment

Wood can be treated with preservatives under pressure in closed vessels, by dipping, hot and cold soak, and diffusion. On the basis of volume of material treated for use in engineered structures, the pressure treatments are most important.

Three pressure systems are standard today: **full-cell** (Bethell), **Lowry,** and **Rueping.** All employ a combination of pressure and vacuum in sequence on material contained in a pressure vessel. The essential difference is the use of an initial vacuum or pressure. The full-cell process draws a vacuum on the charge, then introduces the preservative without breaking the vacuum, so that a maximum of preservative can be forced into the wood. The Lowry system uses atmospheric pressure at the start, and the Rueping process employs a positive initial

pressure. The latter two systems are also called **empty-cell processes** because the air under pressure in the wood will expand at the end of the cycle to force out excess preservative from cell cavities, leaving a minimum retention for maximum penetration. The Rueping process is the most efficient in this respect and is now the principal creosoting process in use in this country. Typical pressure–time cycles for the three processes are shown in Fig. 4. The temperature during the treatment depends mostly on the preservative. Creosote oils are usually used in the range of 180 to 200°F. Salt solutions are used at temperatures from atmospheric to 200°F. Higher temperatures with salts may cause difficulties in reactions with the wood and embrittlement.

Fire-retardant treatments of wood use the same pressure methods and equipment as that used for preservation. Salts similar to those used to protect against fungus attack are employed (see above), but in much greater quantities, up to refusal. This high proportion of inorganic material can have a dulling effect on machine tools. The three principal materials used are chromated zinc chloride (FR), Minalith, and Pyresote. (See also Sec. 12, Fire Protection.)

Allowable working stresses for preservative-treated lumber should be reduced to account for damage due to the treating process. Tests made by the U.S. Forest Products Laboratory of preservative-treated lumber when undergoing bending and compression perpendicular to grain show reductions in stress in extreme fiber from a few percent up to 25 percent, depending on the treating conditions. Compression parallel to grain is affected less and modulus of elasticity very little. The effect on horizontal shear can be estimated by inspection for increase in shakes and checks after treatment. Keeping temperatures, heating periods, and pressures to a minimum for required penetration and retention will hold the loss in working stress to a reasonable figure.

COMMERCIAL LUMBER STANDARDS

Standard abbreviations for lumber description and **size standards** for yard lumber are given in the "Wood Handbook."

Cross-sectional **dimensions** and **section properties** for beams, stringers, joists, planks, and posts are given in Sec. 12., Structural Design of Buildings.

Standard patterns for finish lumber are shown in publications of the grading and dressing rules for the various lumber associations.

Information and **specifications for commercial plywood** are given in Commercial Standards: CS45–55 for Douglas-fir Plywood and CS35–49 for Hardwood Plywood.

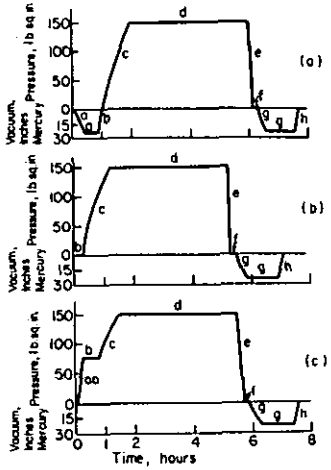

Fig. 4 Typical pressure diagrams for pressure preservative treatment of wood. (*From Hunt and Garratt, "Wood preservation," McGraw-Hill.*) (*a*) *Full-cell process:* *a*, preliminary vacuum period; *b*, filling cylinder with preservative; *c*, pressure rising to maximum; *d*, maximum pressure maintained; *e*, pressure released; *f*, preservative withdrawn; *g*, final vacuum period; *h*, vacuum released. (*b*) *Lowry process:* *b*, filling cylinder with preservative at atmospheric pressure; *c* to *b*, pressure period and final vacuum, as in (*a*). (*c*) *Rueping process:* *aa*, preliminary air pressure applied; *b*, filling cylinder, while pressure is maintained; *c* to *b*, pressure period and final vacuum, as in (*a*). lb/in² × 6,894 = Pa; in Hg × 3,376 = Pa.

NONMETALLIC MATERIALS

by Rienzi B. Parker, Jr.
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ABRASIVES

References: "Abrasives: Their History and Development," The Norton Co. Searle, "Manufacture and Use of Abrasive Materials," Pitman. Heywood, "Grinding Wheels and Their Uses," Penton. "Boron Carbide," The Norton Co. "Abrasive Materials," annual review in "Minerals Yearbook," U.S. Bureau of Mines. "Abrasive Engineering," Hitchcock Publishing Co. Coated Abrasives Manufacturer's Institute, "Coated Abrasives—Modern Tool of Industry," McGraw-Hill. Wick, Abrasives; Where They Stand Today, *Manufacturing Engineering and Management*, vol. 69, no. 4, Oct. 1972. Burls, "Diamond Grinding: Recent Research and Development," Mills and Boon, Ltd., London. Coes, Jr., "Abrasives," Springer-Verlag, New York. *Proceedings of the American Society for Abrasives Methods*, 1971.

Manufactured (Artificial) Abrasives

Manufactured abrasives dominate the scene for commercial and industrial use, because of the greater control over their chemical composition and crystal structure, and their greater uniformity in size, hardness, and cutting qualities, as compared with natural abrasives. Technical advances have resulted in abrasive "machining tools" that are economically competitive with many traditional machining methods, and in some cases replace and surpass them in terms of productivity.

Grains

Manufactured (industrial or synthetic) **diamonds** are produced from graphite at pressures 29.5 to 66.5 × 10^8 N/m² (8 to 18 × 10^8 lb/in²) and temperatures from 1090 to 2420°C (2000 to 4400°F), with the aid of metal catalysts. The shape of the crystal is temperature-controllable, with cubes (black) predominating at lower temperatures and octahedra (yellow to white) at higher. General Electric Co. produces synthetics reaching 0.01 carat sizes and of quality comparable to natural diamond powders. Grade MBG-11 (a blocky powder) is harder and tougher and is used for cutting wheels. Diamond hardness (placed at 10 on the Mohs scale) ranges from 5,500 to 7,000 on the Knoop scale. Specific gravity is 3.521.

Crystalline alumina, as chemically purified Al_2O_3, is very adaptable in operations such as precision grinding of sensitive steels. However, a tougher grain is produced by the addition of TiO_2, Fe_2O_3, SiO_2, ZrO_2. The percentage of such additions and the method of cooling the pig greatly influence grain properties. Advantage is taken of this phenomenon to "custom" make the most desirable grain for particular machining needs. Alumina crystals have conchoidal fracture, and the grains when crushed or broken reveal sharp cutting edges and points. Average properties are: density ~ 3.8, coefficient of expansion ~ 0.81 × 10^{-6}/°C (0.45 × 10^{-6}/°F), hardness ~ 9 (Mohs scale), and melting temperature ~ 2040°C (3700°F). Applications cover the grinding of high-tensile-strength materials such as soft and hard steels, and annealed malleable iron.

Silicon carbide (SiC) corresponds to the mineral moissanite, and has a hardness of about 9.5 (Mohs scale) or 2,500 (Knoop), and specific gravity 3.2. It is insoluble in acid and is infusible but decomposes above 2230°C (4060°F). It is manufactured by fusing together coke and sand in an electric furnace of the resistance type. Sawdust is used also in the batch and burns away, leaving passages for the carbon monoxide to escape. The grains are characterized by great brittleness. Abrasives of silicon carbide are best adapted to the grinding of low-tensile-strength materials such as cast iron, brass, bronze, marble, concrete, stone, and glass. It is available under several trade names such as **Carborundum, Carbolon, Crystolon.**

Boron carbide (B_4C), a black crystal, has a hardness of about 9.32 (Mohs scale) or about 2,800 (Knoop), melts at about 2460°C (4478°F) but reacts with oxygen above 983°C (1800°F), and is not resistant to fused alkalies. Boron carbide powder for grinding and lapping is obtainable in standard mesh sizes to 240, and to 800 in special finer sizes. It is being used in loose grain form for the lapping of cemented-carbide tools. In the form of molded shapes, it is used for pressure blast nozzles, wire-drawing dies, bearing surfaces for gages, etc.

Boron nitride (BN) when produced at extremely high pressures and temperatures forms tiny reddish to black grains of cubic crystal structure having hardness equal to diamond, and moreover is stable to 1930°C (3500°F). Abrasive powders, such as Borazon, are used extensively for coated-abrasive applications as for grinding tool and die steels and high-alloy steels, particularly where chemical reactivity of diamonds is a problem. Ease of penetration and free-cutting action minimize heat generation, producing superior surface integrity.

Crushed steel is made by heating high-grade crucible steel to white heat and quenching in a bath of cold water. The fragments are then crushed to sizes ranging from fine powder to $\frac{1}{16}$ in diam. They are classified as diamond crushed steel, diamond steel, emery, and steelite, used chiefly in the stone, brick, glass, and metal trades.

Rouge and crocus are finely powdered oxide of iron used for buffing and polishing. Rouge is the red oxide; crocus is purple.

Natural Abrasives

Diamond of the of the **bort** variety, crushed and graded into usable sizes and bonded with synthetic resin, metal powder, or vitrified-type bond, is used extensively for grinding tungsten- and tantalum-carbide cutting tools, and also glass, stone, and ceramics.

Corundum is a mineral composed chiefly of crystallized alumina (93 to 97 percent Al_2O_3). It has been largely replaced by the manufactured variety.

Emery, a cheap and impure form of natural corundum which has been used for centuries as an abrasive, has been largely superseded by manufactured aluminum oxide for grinding. It is still used to some extent in the metal- and glass-polishing trades.

Garnet Certain deposits of garnet having a hardness between quartz and corundum are used in the manufacture of abrasive paper. **Quartz** is also used for this purpose. Garnet costs about twice as much as quartz and generally lasts proportionately longer.

Buhrstones and millstones are generally made from cellular quartz. Chasers (or stones running on edge) are also made from the same mineral.

Natural oilstones, the majority being those quarried in Arkansas, are of either the hard or the soft variety. The hard variety is used for tools requiring an extremely fine edge like those of surgeons, engravers, and dentists. The soft variety, more porous and coarser, is used for less exacting applications.

Pumice, of volcanic origin, is extensively used in leather, felt, and woolen industries and in the manufacture of polish for wood, metal, and stone. An artificial pumice is made from sand and clay in five grades of hardness, grain, and fineness.

Infusorial earth or tripoli resembles chalk or clay in physical properties. It can be distinguished by absence of effervescence with acid, is generally white or gray in color, but may be brown or even black. Owing to its porosity, it is very absorptive. It is used extensively in polishing powders, scouring soaps, etc., and, on account of its porous structure, in the manufacture of dynamite as a holder of nitroglycerin, also as a nonconductor for steam pipes and as a filtering medium. It is also known as **diatomaceous silica.**

TOOLS

Grinding Wheels

Vitrified Process In wheels, segments, and other abrasive shapes of this type, the abrasive grains are bonded with a glass or porcelain obtained by mixing the grains with such materials as clays and feldspars in various proportions, molding the wheel, drying, and firing at a temperature of 1370°C (2500°F) approx. It is possible to manufacture wheels as large as 60 in diam by this process, and even larger wheels may be obtained by building up with segments. Most of the grinding wheels and shapes (segments, cylinders, bricks, etc.) now manufac-