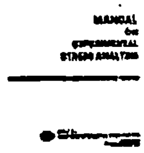

This chapter, fifth in a series of eight, is reprinted from the Third Edition of the SESA's Manual on Experimental Stress Analysis. The remaining chapters will appear in future issues of E/M

Chapter V

Brittle Coatings

by Ferdi B. Stern

Introduction

The brittle-coating method of experimental stress analysis consists of applying a brittle coating on the surface of the part to be tested. Cracks in the coating that appear due to loading the part can be analyzed for direction and magnitude of the surface strains. Normally, ~~the coating cracks at right angles to directions of the maximum tensile strain~~. The coatings can be calibrated to obtain quantitative strain measurements.

Brittle coating has a number of advantageous characteristics. Its effective gage length approaches zero; it gives an overall picture of the strain distribution and highlights areas of stress concentrations; and it is applicable to any mechanical part of the structure, regardless of material, shape, or mode of loading.

Commercially available brittle coatings are used for the following purposes:

1. Locating small areas of high stresses.
2. Determining directions of principal stresses.
3. Measuring the approximate magnitudes of tension- and compression-stress concentrations under static loads.
4. Measuring tension-stress concentrations under dynamic and impact loads.
5. Indicating localized plastic yielding.

The principal uses of brittle coatings are to quickly locate and evaluate the high-stress points in a design, and to obtain principal-stress directions for subsequent placement of electric-resistance strain gages.

There are two principal types of brittle coatings available. One is a series of strain-sensitive coatings made from resins dissolved in solvents so they may be sprayed on the parts to be studied. Plasticizers are added in varying amounts during the formulating process to produce coatings with differing failure characteristics. The coatings are air dried and designed to crack at strain levels on the order of 500 to 700 microstrain. Strains of 1500 μin./in. and above or down to 100 μin./in. and below, can be indicated by proper manipulation of the coatings. Temperature has a significant effect on the sensitivity of the coatings. Humidity has a lesser effect.

The other series are ceramic coatings which are insensitive to temperature changes up to 300°C and are available for use on steel and similar materials. The coating in its liquefied form consists of ceramic powder which is suspended in a carrier. This coating, after being applied to the structural component, must be glazed by firing at approximately 530°C in order to form a continuous brittle coating.

Brittle-coating Techniques

1. *Surface Preparation*—Oil, grease or any material which might affect the bonding of the resin coatings, must be removed. Grinding rough sand castings in the areas of stress concentrations improves the visibility of cracked patterns. Sand or grit blasting is normally required for surface preparation prior to ceramic coating.

2. *Undercoat*— ~~An aluminum undercoat is~~ often used ~~with the air~~-dried coatings to ~~improve the~~ visibility of the crack patterns. No undercoat is used with the ceramic coatings.

3. *Coating Selection*—Resin-base coatings are selected on the basis of temperature and humidity expected at the time of test. Ceramic coatings are selected on the basis of a coefficient of expansion of the material under test.

4. *Coating Application*—Pressure cans or air-spray guns are used to apply both resin-base and ceramic coatings. Color is the normal gage of coating thickness with the resin coatings.

5. *Dry*—Normal drying time for resin coatings is on the order of 24 h to permit sufficient time for solvent release from the coatings and development of coating brittleness. The ceramic coatings are ready for use after they have cooled from the firing temperature.

6. *Calibration*—Calibration bars which have been

Ferdi B. Stern is associated with Magnaflux Corporation, New York, NY 10036.

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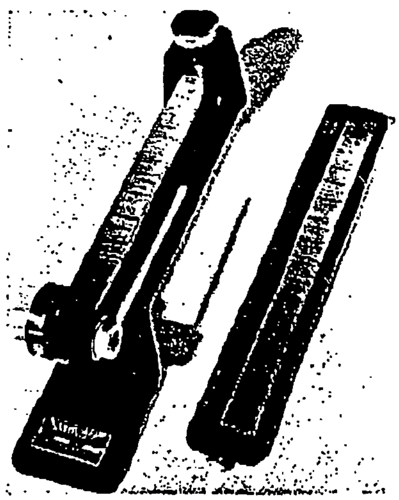


Fig. 5-1—Calibrator and strain scale

Fig. 5-4—Calibration of brittle-coating patterns on a crane hook

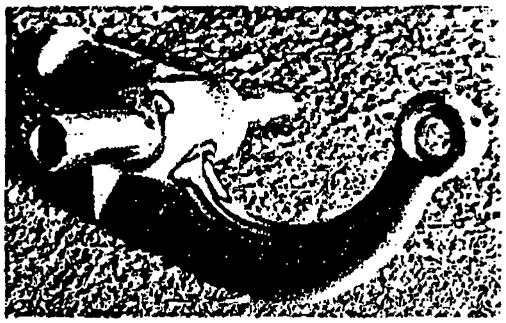


Fig. 5-2—Static-load test of a rocker arm

Fig. 5-3—Brittle-coating cracks enhanced by electrostatic-charge particles

sprayed and dried along with the test parts are loaded as cantilever beams with a known deflection in a calibrating fixture. Strain scales are then used to measure the strain at which the coating begins to crack. (Fig. 5-1) The calibration technique must be used if quantitative strain measurement is required. The calibration devices are also valuable when one is learning the spray techniques. Calibration of the coating also predicts how the coating on a part will behave during a test. It is useful to obtain this information before testing a part and learning that the particular coating is too soft and requires excessive strain to initiate crack patterns. Sensitizing and coloring techniques are also rapidly evaluated by calibration.

TABLE 5-1—MEASURING TENSION STRAINS

(Return to Zero-load Technique)

Test Load (Kg)	Pattern Location (By Area)	Microstrain at 2000-Kg Load	Apparent Stress (MN/m^2) at 2000-Kg Load
1000	None	–	–
0	–	–	–
1250	A	1280*	264.8†
0	–	–	–
1550	A grows	1030	213.1
0	–	–	–
1950	No additional patterns	–	–
0	–	–	–
2440	A grows B added	655	135.9
0	–	–	–
3050	A grows B grows	525	108.3

NOTES: Time to reach load in all cases is 45 s.
Calibration bar loaded in 45 s.
Threshold strain—800 microstrain.
Local strains are assumed proportional to loads.
Modulus of elasticity = 206,897 MN/m^2

* (Typical Calculation) $(800)\frac{2000}{1250} = 1280$

† (Typical Calculation) $(1280 \times 10^{-6}) \times (206{,}897) = 264.8$

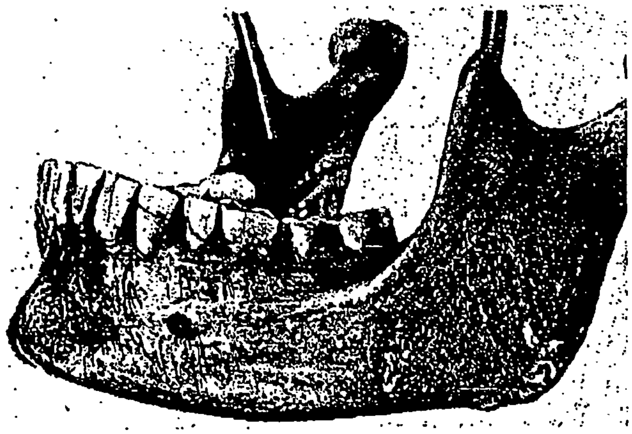


Fig. 5-5—Brittle-coating patterns on a jaw bone

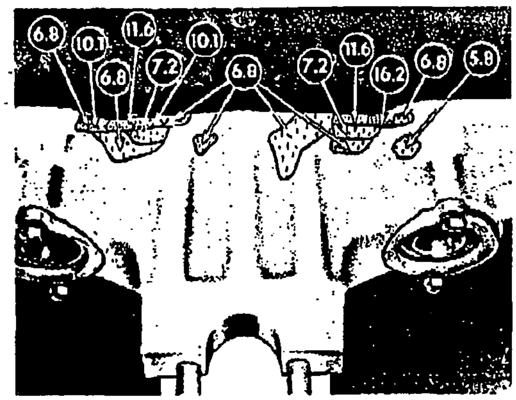


Fig. 5-6—Experimental stress analysis of a truck equalizer saddle by brittle coatings

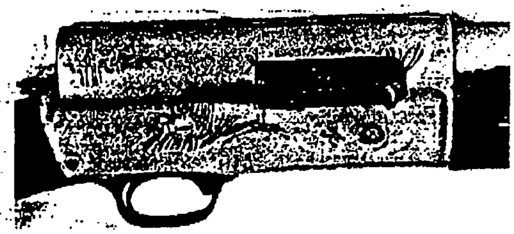


Fig. 5-7—Brittle-coating patterns on a gun produced during firing

7. *Test*—Time required to reach load is a prime consideration in use of the resin coatings. The coatings creep rapidly so loading time should be as short as possible. Temperature changes during tests should be minimized as this also affects coating sensitivity. Oil should be kept off the part as it will attack the resin coating. These limitations do not apply to the ceramic coatings.

8. *Detect and Record Crack Patterns*—Crack patterns in the resin coatings are viewed with oblique lighting (Fig. 5-1). Spread of the patterns with increase in load increments may be marked on the coating and photographed at conclusion of the test as shown in Fig. 5-2. These boundary markers are called 'isoentatics' and represent approximate constant-strain curves. The cracks may be colored with a red dye or they may be brought out by use of an electrostatic-charged-particle technique (Fig. 5-3). The charged particles must be used to show cracks in the ceramic coatings.

9. *Post Clean*—The resin coatings may be removed by scraping, wire brushing, vapor degrease or solvents. The ceramic coats are best removed by sand or grit blasting.

10. *Computations*—Cracks from the calibration bar are compared to those on the part when quantitative data are required (Fig. 5-4). A typical data sheet and computations are shown in Table 5-1.

If the maximum principal stress is substantially larger than the minimum principal stress, and if the coating is calibrated on the same material as used in the structure, then the apparent-stress calculations of Table 5-1 are sufficiently accurate.

More details of brittle-coating technique and safety precautions can be found in the manufacturers' operating instructions.

Typical Applications of Brittle Coatings

Brittle coatings have been used on plastics, wood, paper, rubber, glass, bone (Fig. 5-5), as well as metals.

Tests have been conducted using static loads (Fig. 5-6), impact loads (Fig. 5-7), and dynamic loads (Fig. 5-8).

Ceramic coatings have been used to study tensile stresses due to thermal loads.

Brittle coatings have been used to test parts in the laboratory as well as out-of-doors under field conditions.

Interpretation of Brittle-coating Crack Patterns

An operator quickly becomes familiar with patterns in the coatings that can occur during drying of the coating and prior to load application. 'Drying cracks' are shaped like a valley and generally occur in thick sections of very

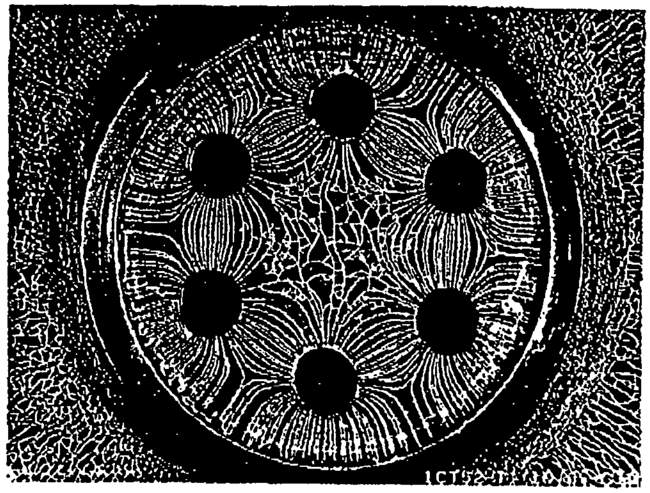


Fig. 5-8—Patterns produced in a ceramic brittle coating on a turbine disk spun at high speeds

brittle coatings. 'Crazing cracks' have a random orientation and are caused by exposure of the coating to low temperatures.

Isolated patterns occurring at low loads in mild-steel structures can be caused by yielding when locked-up stresses from welding relieve themselves.

The appearance of the brittle-coating pattern along the slip planes during a yielding of a mild-steel cylinder under compression loading is shown in Fig. 5-9.

Large strains cause spalling of the coating in compression and flaking in tension as shown in Fig. 5-10.

Isolated patterns sometimes occur on the surface of a part due to stress concentrations from blow holes, shrink cracks, fatigue cracks and other discontinuities. These should have been detected by use of nondestructive-testing methods prior to the experimental-stress-analysis work.

Unique patterns during a brittle-coating test may be caused by a change in loading of the structure. The operator should be alert for this condition.

A random pattern is produced from an equal two-dimensional tension field.

Orthogonal patterns in the resin-base coatings may be produced by first loading the part to produce cracks from tensile strains. If the load is reversed to create compression strains, and the coating is sensitized by cooling when the part is under the compression load, a set of patterns normal to the initial ones can be produced.

Under impact loading, peak tensile strains are recorded by the brittle coatings. No time relationships are given by the coatings, so other types of gages must be used to obtain time relationships of the wave trains. The brittle-coating patterns assist in location of the gages.

Brittle coatings serve as a recording strain gage. The actual cracks in the coating, due to the strains in the structure, give a striking, visual picture of the manner in which the part is deflecting.

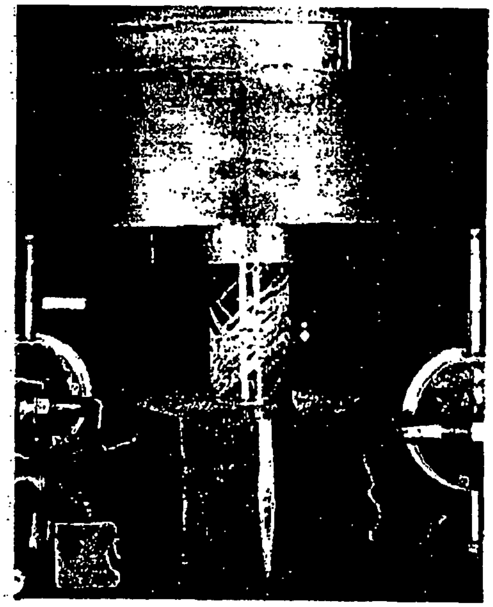


Fig. 5-9—Brittle-coating patterns on a mild-steel compression specimen during yielding

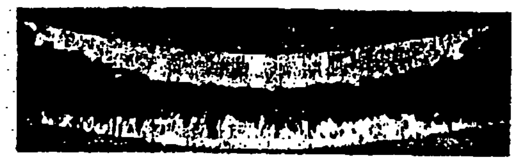


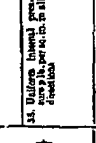
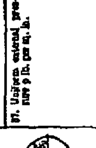
Fig. 5-10—Spalling and flaking of a resin-base brittle coating due to large strains

Suggested List of Reading References

1. Cumulative Index Proc. SESA, (Brittle Coatings), 1 (1)—3 (2), 42 (1943-1973).

2. Principles of Stresscoat, Brittle Coatings Stress Analysis, Magnaflux Corp., 3rd edition (1971).

TABLE XIII.—FORMULAS FOR STRESSES AND DEFORMATIONS IN PRESSURE VESSELS.—(Continued)

Form of vessel	Manner of loading and Case No.	Formulas
		Thick vessels—wall stresses s_1 (longitudinal), s_2 (circumferential) and s_3 (radial)
	33. Uniform internal radial pressure p lb. per sq. in. (longitudinal pressure zero or externally balanced)	$s_1 = 0$ $\quad s_2 = p\frac{a^2(b^2+r^2)}{r^2(b^2-a^2)}$. Max $s_2 = p\frac{b^2+a^2}{b^2-a^2}$ at inner surface $s_3 = -p\frac{a^2(b^2-r^2)}{r^2(b^2-a^2)}$. Max $s_3 = -p$ at inner surface; max $s_s = p\frac{b^2}{b^2-a^2}$ at inner surface $\Delta a = p\frac{a}{E}\left(\frac{b^2+a^2}{b^2-a^2}+\nu\right)$; $\Delta b = p\frac{b}{E}\left(\frac{2a^2}{b^2-a^2}\right)$
	34. Uniform external radial pressure p lb. per sq. in.	$s_1 = 0$ $\quad s_2 = -p\frac{b^2(a^2+r^2)}{r^2(b^2-a^2)}$. Max $s_2 = -p\frac{2b^2}{b^2-a^2}$ at inner surface $s_3 = -p\frac{b^2(r^2-a^2)}{r^2(b^2-a^2)}$. Max $s_3 = -p$ at outer surface; max $s_s = \frac{1}{2}$ max s_2 at inner surface $\Delta a = -p\frac{a}{E}\left(\frac{2b^2}{b^2-a^2}\right)$; $\Delta b = -p\frac{b}{E}\left(\frac{a^2+b^2}{b^2-a^2}-\nu\right)$
 Cylindrical	35. Uniform internal pressure p lb. per sq. in. in all directions	$s_1 = p\frac{a^2}{b^2-a^2}$. s_2 and s_3 same as for Case 33 110: 444 $\Delta a = p\frac{a}{E}\left[\frac{b^2+a^2}{b^2-a^2}-\nu\left(\frac{a^2}{b^2-a^2}-1\right)\right]$; $\Delta b = p\frac{b}{E}\left[\frac{a^2}{b^2-a^2}(2-\nu)\right]$; $p_u = s_u \ln\frac{b}{a}$
	36. Uniform internal pressure p lb. per sq. in.	$s_1 = s_2 = p\frac{a^3(b^3+2r^3)}{2r^3(b^3-a^3)}$. Max $s_1 = $ max $s_2 = p\frac{b^3+2a^3}{2(b^3-a^3)}$ at inner surface $s_3 = -p\frac{a^3(b^3-r^3)}{r^3(b^3-a^3)}$. Max $s_3 = -p$ at inner surface; max $s_s = p\frac{3b^3}{4(b^3-a^3)}$ at inner surface (Ref. 2) $\Delta a = p\frac{a}{E}\left[\frac{b^3+2a^3}{2(b^3-a^3)}(1-\nu)+\nu\right]$; $\Delta b = p\frac{b}{E}\left[\frac{3a^3}{2(b^3-a^3)}(1-\nu)\right]$. Yield pressure $p_y = \frac{2s_y}{3}\left(1-\frac{a^3}{b^3}\right)$ (Ref. 20)
 Spherical	37. Uniform external pressure p lb. per sq. in.	$s_1 = s_2 = -p\frac{b^3(a^3+2r^3)}{2r^3(b^3-a^3)}$. Max $s_1 = $ max $s_2 = -p\frac{3b^3}{2(b^3-a^3)}$ at inner surface $s_3 = -p\frac{b^3(r^3-a^3)}{r^3(b^3-a^3)}$. Max $s_3 = -p$ at outer surface $\Delta a = -p\frac{a}{E}\left[\frac{3b^3}{2(b^3-a^3)}(1-\nu)\right]$; $\Delta b = -p\frac{b}{E}\left[\frac{a^3+2b^3}{2(b^3-a^3)}(1-\nu)-\nu\right]$ (Ref. 3)

73. Thin Vessels under External Pressure.—All formulas given in Table XIII for thin vessels under uniform pressure are for internal pressure. They will apply equally to cases of external pressure if p is given a negative sign, but the stresses so found are significant only when the pressure is insufficient to cause failure through *elastic instability*, that is, through buckling that starts at stresses within the proportional limit. This type of failure is not considered here; it is discussed in Chap. 14, and formulas for the critical pressures or stresses producing it are given in Table XVI.

A vessel of moderate thickness may collapse under external pressure at stresses above the proportional limit but below the yield point, its behavior being comparable to that of a short column. The problem of ascertaining the pressure that produces failure of this kind is of special interest in connection with cylindrical vessels and pipes, and under Case 1 a formula is given that is applicable to this problem. In Ref. 8 charts are given that provide a solution to this same problem.

74. Thick Vessels under Internal or External Pressure.—If the wall thickness of a vessel is more than about one-tenth the radius, the meridional and hoop stresses cannot be considered uniform throughout the thickness of the wall, and the radial stress cannot be considered negligible. These stresses in thick vessels, here called *wall stresses*, must be found by formulas that are quite different from those used in finding membrane stresses in thin vessels.

It can be seen from the formulas for Cases 33 and 35 that the stress s_2 at the inner surface of a thick cylinder approaches p as the ratio of outer to inner radius approaches infinity. It is, therefore, apparent that if the stress is to be limited to some specified value s, the pressure must never exceed $p = s$, no matter how thick the wall is made. To overcome this limitation, the material at and near the inner surface must be put into a state of initial compression; this can be done by shrinking on one or more jackets (as explained in Art. 11 and in the examples below), or by subjecting the vessel to a high internal pressure that stresses the inner part into the plastic range and, when removed, leaves residual compression there and residual tension in the outer part. This procedure is called *autofrettage*, or self-hooping. If many successive jackets are superimposed on the original tube by shrinking or wrapping, the resulting structure is called a *multilayer* vessel. Such construction has certain advantages, but it should be noted that the formulas for hoop stresses are based on the assumption of an isotropic material; in a multilayered vessel the effective radial modulus of elasticity is less than the tangential modulus, and in consequence the hoop stress at and near the outer wall is less than the formula would indicate. Consequently, the outer layers of material contribute less to the strength of the vessel than might be supposed.

The tabulated formulas for elastic membrane stresses are accurate for both thin and thick vessels, but the formulas for predicted yield and bursting pressures, especially the former, do not always agree closely with experimental results (Refs. 21, 34, 35, 37, 39). The expressions for p_y given in the table are based on the minimum strain-energy theory of elastic failure. The expression for bursting pressure $p_u = 2s_u\left(\frac{b-a}{b+a}\right)$, commonly known as the "mean diameter" formula, is essentially empirical, but is given because it agrees reasonably well with experiment for both thin and thick vessels and is convenient to use. For very thick vessels the formula $p_u = s_u \log_e (b/a)$ is preferable. Greater accuracy can be obtained by using with this formula a multiplying factor that takes into account the strain-hardening properties of the material (Refs. 20, 37). With the same objective, Faupel (Ref. 39) proposed (with different notation) the formula $p_u = \frac{2s_y}{\sqrt{3}} \log_e \frac{b}{a}\left(2 - \frac{s_y}{s_u}\right)$. A rather extensive discussion of bursting pressure is given in Ref. 38, which presents a tabulated comparison between bursting pressures as calculated by a number of different formulas and as determined by actual experiment.

Example

At the powder chamber, the inner radius of a 3-in. gun tube is 1.605 in., the outer radius is 2.425 in. It is desired to shrink a jacket on this tube so as to produce a radial pressure between tube and jacket of 7600 lb. per sq. in. The outer radius of this jacket is 3.850 in. It is required to determine the difference between the inner radius of the jacket and the outer radius of the tube in order to produce the desired pressure, to calculate the stresses in each part when assembled, and to calculate the stresses in each

part when the gun is fired, generating a powder pressure of 32,000 lb. per sq. in.

Solution.—Using the formulas for Case 34, it is found that for an external pressure of 7600 the stress s_1 at the outer surface of the tube is $-19{,}430$, the stress s_1 at the inner surface is $-27{,}050$, and the change in outer radius $\Delta b = -0.001385$. It is found that for an internal pressure of 7600 the stress s_1 at the inner surface of the jacket is $+17{,}630$, the stress s_1 at the outer surface is $+10{,}050$, and the change in inner radius $\Delta a = +0.001615$. (In making these calculations the inner radius of the jacket is assumed to be 2.425 in.) The initial difference between the inner radius of the jacket and outer radius of the tube must be equal to the sum of the radial deformations they suffer, or $0.001385 + 0.001615 = 0.0030$. Therefore the initial radius of the jacket should be $2.425 - 0.0030 = 2.422$ in.

The stresses produced by the powder pressure are calculated at the inner surface of the tube, at the common surface of tube and jacket ($r = 2.425$) and at the outer surface of the jacket. These stresses are then superposed on those found above. The calculations are as follows:

For the tube:

$$s_1 = +32{,}000\left(\frac{3.85^2 + 1.605^2}{3.82^2 - 1.605^2}\right) = +45{,}450$$
$$s_2 = +32{,}000$$

For tube and jacket:

$$s_1 = +32{,}000\left(\frac{1.605^2}{2.425^2}\right)\left(\frac{3.85^2 + 2.425^2}{3.85^2 - 1.605^2}\right) = +23{,}500$$
$$s_2 = +32{,}000\left(\frac{1.605^2}{2.425^2}\right)\left(\frac{3.85^2 - 2.425^2}{3.85^2 - 1.605^2}\right) = +10{,}200$$

For the jacket:

$$s_1 = +32{,}000\left(\frac{1.605^2}{3.85^2}\right)\left(\frac{3.85^2 + 3.85^2}{3.85^2 - 1.605^2}\right) = +13{,}500$$

These are the stresses due to the powder pressure. Superposing the stresses due to the shrinkage, we have as the resultant stresses:

At inner surface of tube,

$$s_1 = -27{,}050 + 45{,}450 = +18{,}400 \text{ lb. per sq. in.}$$
$$s_2 = 0 + 32{,}000 = +32{,}000 \text{ lb. per sq. in.}$$

At outer surface of tube,

$$s_1 = -19{,}430 + 23{,}500 = +4070 \text{ lb. per sq. in.}$$
$$s_2 = +7600 + 10{,}200 = +17{,}800 \text{ lb. per sq. in.}$$

At inner surface of jacket,

$$s_1 = +17{,}630 + 23{,}500 = +41{,}130 \text{ lb. per sq. in.}$$
$$s_2 = +7600 + 10{,}200 = +17{,}800 \text{ lb. per sq. in.}$$

75. Design Formulas for Conventional Pressure Vessels.—As can be seen from the example of Art. 72, the discontinuity stresses