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THERMAL EXPANSION, MODULUS, AND MUZZLE DRIFT

P. J. COTE

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US ARMY ARMAMENT RESEARCH, DEVELOPMENT AND ENGINEERING CENTER
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BENÉT LABORATORIES
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Drifts in gun muzzle orientation are commonly observed during firing and are generally attributed to thermal stresses generated by temperature differences in different parts of the tube. Thermal shrouds are used to reduce the amplitude of such drifts. The present report addresses drifts that may originate from overall tube temperature rather than temperature differences. In these cases, the original muzzle orientation is recovered only when the tube returns to its original temperature. One familiar effect is the deflection from tube weight, known as muzzle droop, which increases in magnitude with firing. Another possible source for effects of this type is asymmetry in properties that may originate from plastic bending during tube straightening. The physical properties that govern such effects are the thermal expansion coefficient and the temperature dependence of the modulus.

One of the main objectives of this report is to clarify some of the formalism related to muzzle drift from uniform heating. The question of how to treat the effect of stress on the thermal expansion coefficient is addressed in detail, since this is a quantity that is rarely measured. It is shown that the effect of stress on thermal expansion can be formulated in the more familiar terms of the temperature dependence of the elastic modulus. The concepts are illustrated with applications to tensile testing and muzzle droop. Suggested sources for muzzle "walk" from the tube straightening process are also discussed.

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INTRODUCTION

The topic of gun tube muzzle drift from thermal gradients generated by solar heating and convection is generally well understood. Thermal shrouds have proven effective in reducing such effects (refs 1,2). The present study was motivated by reports (ref 3) that some muzzle drifts appear to correlate with overall tube temperature rather than thermal gradients; there is speculation that the tube straightening process may be responsible for this type of muzzle drift (termed muzzle "walk"). A familiar example where muzzle orientation changes with tube temperature is muzzle droop: a change in the orientation of the muzzle occurs on heating, independent of convection effects, because of the external moment from the weight of the tube itself and the temperature dependence of the modulus (or, equivalently, the stress dependence of the expansion coefficient).

One purpose of this report is to clarify the basic concepts regarding the important role of stress on thermal expansion and the connection between the thermal expansion coefficient and the temperature dependence of the modulus. Rosenfield and Averbach (ref 4) have experimentally confirmed the theoretical relation between derivatives of the expansion coefficient and the elastic modulus. A key point that is not generally recognized is that the assumption of path independence of the strain permits formulation of the problem in terms of the effect of stress on expansion coefficient or, equivalently, in terms of the temperature dependence of the elastic modulus. This provides an answer to the question of how to treat the effect of stress on the expansion coefficient. The concepts are illustrated through several elementary examples: muzzle droop and elevated temperature tensile testing.

In principle, long-term muzzle drifts can also arise from nonuniform temperature properties of the steel within the tube. Such effects can, in principle, arise from asymmetric plastic deformation or from different responses to tensile and compressive deformation in the tube straightening process, for example. Rosenfield and Averbach (ref 4) observed that the thermal expansion coefficient of steel is affected by plastic deformation.

Similarly, the temperature dependence of the modulus can be affected by plastic deformation. For example, nickel and iron-nickel alloys show dramatic changes in modulus with deformation because of magnetoelastic effects; with low-nickel steels, such as gun steels, however, the effect from this source is observed to be small (ref 5).

With the increasing premium on gun accuracy, there is a need to address the more subtle contributions to muzzle motion. With the exception of the work of Rosenfield and Averbach (ref 4), there is little discussion in the literature on the relationship between modulus and thermal expansion. Since the effects are small and complicated, misconceptions are possible, so a review of the basic concepts may be helpful. To that end, a development of the elementary formalism is included below, along with a discussion of examples relevant to muzzle drift.

THEORY

As long as the loading is elastic (i.e., plastic deformation and anelastic effects are negligible), and the temperature remains below the point where annealing or transformation effects are important, *the strain ε can be assumed to depend uniquely on the independent coordinates, stress σ, and temperature T.* The total differential $d\varepsilon$ is then given by

$$d\epsilon = \frac{\partial \epsilon}{\partial \sigma}\Big|_T d\sigma + \frac{\partial \epsilon}{\partial T}\Big|_\sigma dT \tag{1}$$

The linear thermal expansion coefficient α is appropriate for the one- and two-dimensional problems considered here, and is defined as

$$\alpha = \left(\frac{\partial \epsilon}{\partial T}\right)_\sigma \tag{2}$$

The isothermal elastic modulus E(T) is defined as

$$\frac{1}{E(T)} = \left(\frac{\partial \epsilon}{\partial \sigma}\right)_T \tag{3}$$

Equation 1 can thus be rewritten as

$$d\epsilon = \frac{d\sigma}{E(T)} + \alpha(\sigma)dT. \tag{4}$$

The assumption that ε is a unique function of T and σ requires that the line integral of $d\varepsilon$ be path-independent. As shown below, *this requirement imposes a connection between the expansion coefficient and the modulus.* For a homogeneous system under uniform stress and temperature, Eq. 4 can conveniently be integrated along two different paths (path 1 = dashed line in Figure 1; path 2 = solid line in Figure 1) in the T - σ plane. It is assumed that the temperature difference $\delta T = T_1 - T_0$ and stress change $\delta\sigma = \sigma_1 - \sigma_0$ are sufficiently small that only linear terms in α and E need be considered. (The more general results will be stated in integral form.) For many examples of interest, T_0 is room temperature and σ_0 is zero.

For path 1, the system is first heated to T_1 and the stress is then increased to σ_1, giving

$$\epsilon(T_1,\sigma_1) = \int_{path1} d\epsilon = \alpha(\sigma_0)\delta T + \frac{\delta\sigma}{E(T_1)}. \tag{5}$$

For path 2, the stress increases to σ_1 and the system is then heated to T_1. $\varepsilon(T_1,\sigma_1)$ is given as

$$\epsilon(T_1,\sigma_1) = \int_{path2} d\epsilon = \alpha(\sigma_1)\delta T + \frac{\delta\sigma}{E(T_0)}. \tag{6}$$

Path independence requires that the strains in Eqs. 5 and 6 be equal so that

$$\alpha(\sigma_0)\delta T + \frac{\delta\sigma}{E(T_1)} = \alpha(\sigma_1)\delta T + \frac{\delta\sigma}{E(T_0)}. \tag{7}$$

A Taylor series expansion to first order on α about σ_0 gives

$$\alpha(\sigma_1)=\alpha(\sigma_0)+\frac{\partial\alpha}{\partial\sigma}\delta\sigma \tag{8}$$

Similarly, expanding 1/E about T_0 gives

$$\frac{1}{E(T_1)}=\frac{1}{E(T_0)}+\frac{\partial}{\partial T}\left(\frac{1}{E(T)}\right)\delta T. \tag{9}$$

Substituting into Eq. 7 gives

$$\alpha(\sigma_1)=\alpha(\sigma_0)+\frac{\partial}{\partial T}\left(\frac{1}{E(T)}\right)\delta\sigma, \tag{10}$$

and

$$\frac{1}{E(T_1)}=\frac{1}{E(T_0)}+\frac{\partial\alpha}{\partial\sigma}\delta T, \tag{11}$$

and

$$\frac{\partial}{\partial T}\left(\frac{1}{E}\right)=\frac{\partial\alpha}{\partial\sigma}. \tag{12}$$

The above detailed development provides several equations that are needed for the discussion section; however, a simpler and more general proof for Eq. 12 is available: path independence implies that the line integral of dε (Eq. 1) around any closed path is zero; under this circumstance, Green's theorem requires

$$\frac{\partial}{\partial T}\left[\left(\frac{\partial\varepsilon}{\partial\sigma}\right)_T\right]_\sigma=\frac{\partial}{\partial\sigma}\left[\left(\frac{\partial\varepsilon}{\partial T}\right)_\sigma\right]_T \tag{13}$$

Equation 13 is called the "integrability condition" for the state function $\varepsilon(T,\sigma)$. Substituting the definitions for α and 1/E yields Eq. 12.

To estimate the effect of stress on the expansion coefficient, one can use Eq. 12 in Eq. 8, giving

$$\alpha(\sigma_1)=\alpha(\sigma_0)+\frac{\partial}{\partial T}\left(\frac{1}{E}\right)\delta\sigma. \tag{14}$$

Since E usually decreases with T, the thermal expansion coefficient will generally increase under a tensile load and decrease under a compressive load. To first order, the magnitude of the change in thermal expansion coefficient will vary linearly with the magnitude of the stress.

DISCUSSION

Consequences of Path Independence

Path independence provides the two equivalent solutions to Eq. 1 given by Eqs. 5 and 6. For convenience, it is assumed here that the initial temperature is room temperature and the initial stress is zero. The strain, in an element of volume subjected to δT and $\delta\sigma$, can be obtained by using *either* the zero stress value for α and the temperature-dependent E *or* the room temperature value for E and the stress-dependent value of α. Although this follows formally from path independence, Figure 2 shows the physical interpretation for the connection between stress dependence of the expansion coefficient and the temperature dependence of the modulus. (The origin of thermal expansion is the asymmetry in the interatomic potential V that causes the equilibrium positions to vary with temperature along the diagonal lines labeled σ_0 and σ_1 for the two different stress levels.) The effect of stress on α and the effect of temperature on E are simply different manifestations of the same general phenomenon.

One practical application involves the analysis of data from standard tensile testing at various temperatures. Equation 7 applies directly to a specimen that is subjected to both uniaxial stress and temperature. Specifically, path independence allows the fiction that the measured strain originated from either path 1 (thermal expansion at zero stress followed by an elastic strain at the final temperature), or path 2 (elastic strain at room temperature followed by thermal expansion under stress to the final temperature), and this gives the correct value for ε even if neither path was taken in the actual experiment. In other words, the strain that occurs when a specimen under stress is heated can be interpreted as originating from a stress-modified thermal expansion coefficient or a temperature-modified modulus. This fact is not generally appreciated.

For an estimate of the size of the effects one may encounter during tensile testing, for example, assume a steel specimen is loaded to 200 Ksi in a furnace at 300°C above ambient, $\alpha(0)=10^{-5}$/C, and that the average reduction in E for this δT is approximately 9 percent (ref 6). For a one-inch gage length, the thermal expansion from $\alpha(0)$ is 0.0030 inch. The room temperature elastic strain from the 200 Ksi load is 0.0067 inch (assuming $E=30\times10^6$ psi). The temperature rise causes an additional 9 percent in elastic strain (0.0006 inch) because of the modulus reduction; however, this can be interpreted *according to taste* as arising from either the temperature dependence of the modulus or the stress dependence of the expansion coefficient. To illustrate, the expansion coefficient approximated from Eq. 14 for the 200 Ksi load is 12 microinches/(inch C), giving a thermal expansion of 0.0036 inch, which is a 0.0006-inch increase over the unstressed value; as expected, this increase is equal to the increase in strain estimated from the temperature dependence of the modulus (0.0006 inch). The magnitude is small because of the small gage length, but the following shows that the effect is significant for long lengths.

Muzzle droop is the other example used to illustrate these concepts. Assume the problem can be approximated by the elementary beam equations for a uniform cantilevered thin beam with moment of inertia I, and length L aligned along the x-axis, under an external moment M perpendicular to the x-y plane. The stress distribution is given by

$$\sigma_x = \frac{My}{I}. \tag{15}$$

Selecting path 1 to obtain the strain for the thin element of volume subjected to stress σ_x and temperature T_1 gives

$$\epsilon_x = \int_{path1} d\epsilon = \frac{My}{E(T_1)I} + \alpha(0)\delta T. \tag{16}$$

Along this path, the entire beam is viewed as uniformly thermally expanded in the unstressed condition and subsequently bent at temperature by application of the moment. The additional bending beyond room temperature arises from the change in E due to δT.

Selecting path 2, the strain is given by

$$\epsilon_x = \int_{path2} d\epsilon = \frac{My}{E(T_0)I} + \alpha(\sigma_x)\delta T. \tag{17}$$

Along this path, the beam is initially bent at room temperature, and it is the subsequent heating through δT in the presence of a stress-dependent expansion coefficient that produces the additional bending. The additional strains on heating along the two paths are expected to be identical. This can be shown by first substituting Eq. 10 into Eq 17 as follows:

$$\epsilon_x = \frac{My}{E(T_0)I} + \alpha(0)\delta T + \frac{\partial}{\partial T}\left(\frac{1}{E(T)}\right)\sigma_x \delta T. \tag{18}$$

Then substituting Eqs. 9 and 15 into Eq. 18 gives

$$\epsilon_x = \frac{My}{I}\left[\frac{1}{E(T_0)} + \frac{\partial}{\partial T}\left(\frac{1}{E(T)}\right)\delta T\right] + \alpha(0)\delta T = \frac{My}{E(T_1)} + \alpha(0)\delta T. \tag{19}$$

Equation 19 shows that the bending produced along path 2 is identical to that from path 1 (Eq. 16).

The interpretation of the origin of the additional bending from δT in a stressed beam is again primarily *a matter of convenience*. Since the relevant data of this type obtained from tensile tests, beam resonance experiments, and ultrasonics measurements are generally presented in terms of E(T) rather than the equivalent $\alpha(\sigma)$, it is easier to use the former. Thus, temperature dependences can be addressed using the standard beam solutions derived from Eq. 15 by simply including a temperature-dependent E and a uniform thermal expansion computed from $\alpha(0)$, as in the uniaxial case. The same arguments apply for the more general cases.

For the muzzle droop problem, one can therefore use the standard solution of a cantilevered beam with total weight w by explicitly including E(T), L(T), and I(T). The end deflection D(T) is given by

$$D(T)=\frac{wL^3}{8E(T)I}, \tag{20}$$

where $L = L_0(1+\alpha(0)(T-T_0))$, and $I = I_0(1+\alpha(0)(T-T_0))^4$.

For a rough estimate of the expected muzzle droop in gun tubes from this effect, assume a cantilevered uniform cylinder of 15-foot length, 4-inch inner diameter, 6-inch outer diameter, and $\delta T=300°C$. The computed room temperature droop is 0.380 inch in accordance with known room temperature values for gun tubes. The 9 percent reduction in E on heating increases the muzzle droop by 0.034 inch. The $\alpha(0)$ terms tend to cancel each other and a slight decrease in droop is contributed from this source (-0.001 inch). (This is the reverse of the tensile testing example discussed above where the contribution from the modulus change on heating was much smaller than the $\alpha(0)$ contribution to the total strain.) The net predicted muzzle droop (0.033 inch) on heating is comparable in size to deflections produced in solar heating experiments on gun tubes (refs 1,2) and therefore cannot be neglected. Since the muzzle droop in this case is due to uniform heating, shrouds will have little effect on its magnitude.

An estimate of the magnitude of the effect on gun accuracy can be obtained from the derivative of the deflection evaluated at L

$$\frac{dD}{dx}\Big|_{x=L}=\frac{wL^2}{6EI}=\frac{4}{3}\frac{D}{L}. \tag{21}$$

The predicted drop in projectile position in 1000 meters from the room temperature droop is 2.7 meters. The additional 9 percent drop expected on heating through 300°C is 0.24 meter.

Tube Straightening Effects

The topic of possible long-term muzzle drift originating from tube straightening is addressed in this section. Short-term effects from temperature transients are not considered here. (Data from thermal shroud studies (refs 1,2) suggest that temperature transients in large caliber gun tubes decay exponentially with a time constant of approximately 10 minutes). As indicated earlier, a possible source for the long-term phenomenon of muzzle "walk" is a difference in thermal expansion coefficient along the cross section of the tube caused by nonuniform plastic deformation (i.e., differences in the magnitude and direction of the plastic flow in tension and compression) during straightening. Plastic deformation in tension is reported to produce changes of the order of 5 percent in the expansion coefficient of steel (ref 4).

The source of the tube deflection from the plastic deformation differs from the thermal expansion and modulus effect examples considered earlier where nonuniform elastic loading generated the temperature-dependent muzzle motion. As in a bi-metallic strip, an expansion coefficient difference (i.e., difference in $\alpha(0)$) within the tube will set up temperature-dependent thermal stresses that will produce temperature-dependent deflections. A change in expansion coefficient can be treated, for convenience, as a change in temperature for a given element of volume. So a difference of 5 percent between the top and bottom of a tube is equivalent to a temperature difference of 15°C for a tube heated through 300°C. This is similar to the magnitude of the temperature differences recorded in solar heating experiments on gun tubes (refs 1,2), so comparable deflections are therefore possible.

Nonuniformities in plastic deformation from the straightening process might also produce different temperature dependences in the moduli in the different regions of the tube. Any such differences will produce temperature-dependent tube deflections in the presence of residual axial stresses, as the temperature-dependent differential in the strains is accommodated.

In summary, the consequences of path independence of the strain were reviewed, and the connection between temperature dependence of the modulus and the stress dependence of the expansion coefficient was described. The question of how to treat the effect of stress on thermal expansion coefficient is shown to have a simple solution as long as the system remains within the elastic limit. Elevated temperature tensile testing and muzzle droop were discussed to illustrate the basic concepts. On the topic of long-term muzzle "walk" from tube straightening, published data shows that plastic deformation can affect the expansion coefficient, so this may be one source of the reported muzzle "walk." Formal studies of the muzzle "walk" phenomenon itself are needed along with careful measurements of deformation effects on expansion coefficient and modulus before firm conclusions can be drawn regarding the possible deleterious role of straightening on accuracy.

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$$d\varepsilon = \alpha\, dT + d\sigma / E \quad \Rightarrow \quad \begin{aligned} \varepsilon &= \alpha(\sigma_0)\delta T + \delta\sigma / E(T_1) \\ \varepsilon &= \alpha(\sigma_1)\delta T + \delta\sigma / E(T_0) \end{aligned}$$

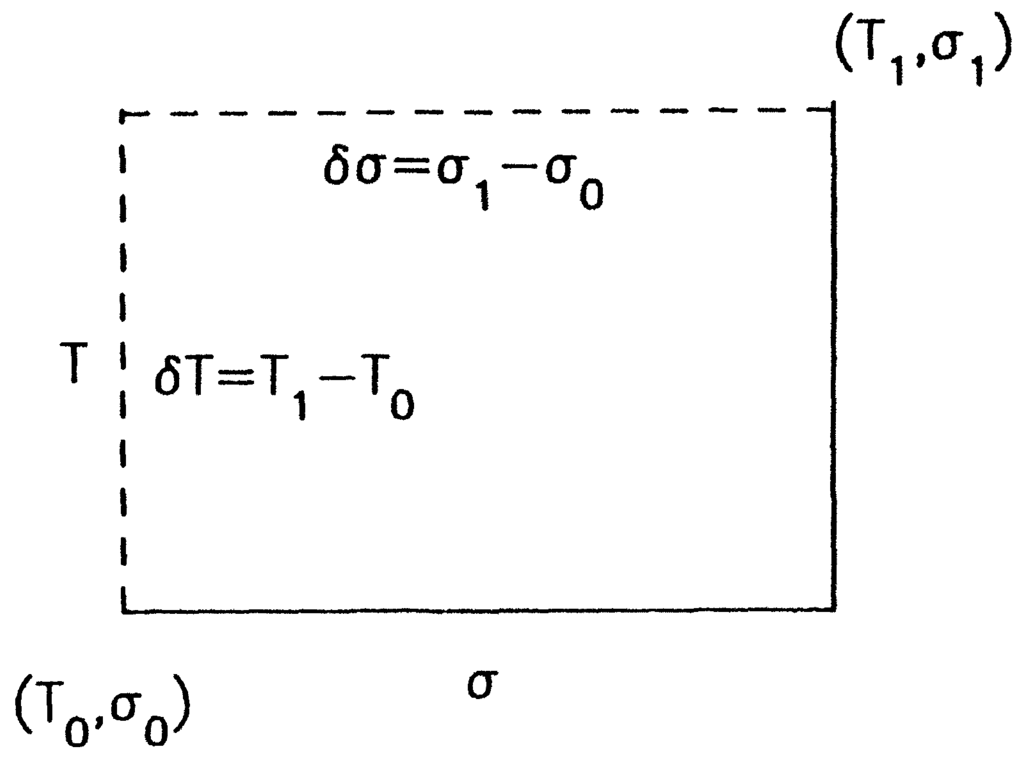

Figure 1. Illustration of path 1 (dashed line) and path 2 (solid line) in the T - σ plane. Path independence requires that the strain computed along both paths be equal.

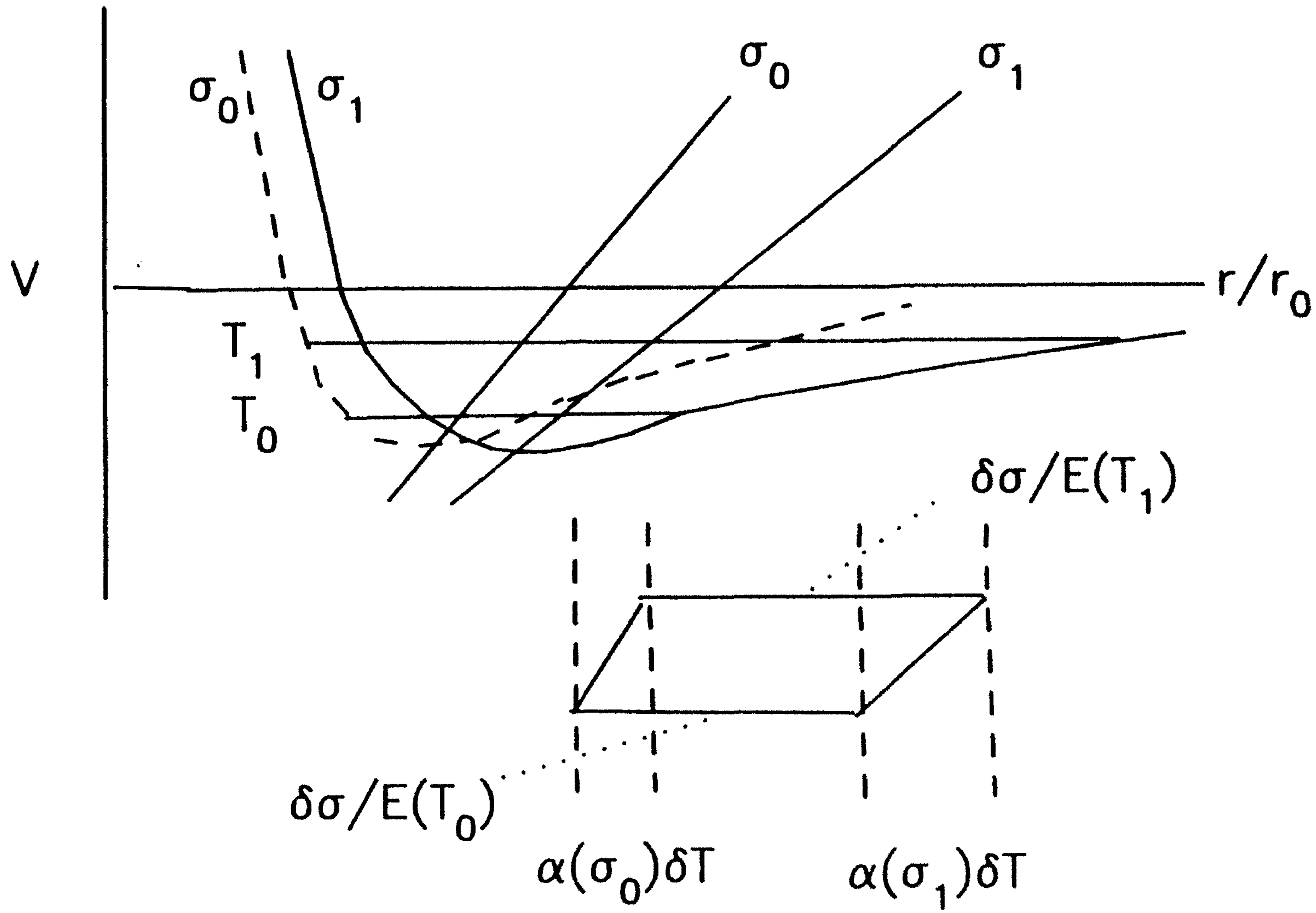

Figure 2. The connection between expansion coefficient and modulus in terms of the influence of stress on the asymmetric interatomic potential V. The equilibrium interatomic spacing is r_0. The diagonal lines indicate the shift in equilibrium position with temperature for the two stress levels.

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