PRESSURE-STRAIN-TEMPERATURE RELATIONSHIP IN SHOCK LOADED CYLINDRICAL SAMPLES OF 304 STAINLESS STEEL

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PRESSURE-STRAIN-TEMPERATURE RELATIONSHIP IN SHOCK LOADED CYLINDRICAL SAMPLES OF 304 STAINLESS STEEL

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Résumé : On décrit l'évolution de la température résiduelle déduite des relations pression-déformation pour un échantillon cylindrique axisymétrique d'acier inoxydable 304. Des explosions axisymétriques conduisent à des relations non uniformes entre pression déformation et température encore incomplètement comprises. Cet article décrit chaque contribution de la température et l'effet notable induit sur l'échantillon.

Abstract The residual temperature resulting from pressure-strain relationships in an axisymmetric cylindrical sample of 304 stainless steel are described. Axisymmetric implosions result in nonuniform pressure-strain-temperature combinations that need to be better understood. This paper describes each temperature contribution and the net effect on the sample.

1. Introduction

Specific features inherent in high dynamic pressures, namely changes in density, electric phenomena, thermodynamic conditions, and plastic deformation in the shock wave front, can result in a series of state changes in the structure of the material undergoing high shock pressure events.

Initial observations on temperature effects resulted not only in the shocked samples being hot, but observations of actual melting of the samples undergoing these shock events. For some time it has been well known that concomitant temperature effects were manifested in and resulted from shock pressures. The development and discussions of this phenomenon are given in /1/. In particular, as the pressure increased, so did the temperature. Based on experiments and calculations, the resultant temperature rise is associated with an adiabatic, ΔT_A and a residual, ΔT_r temperature, and have for a number of materials been tabulated /2/. These data are for zero strain conditions. However, for situations wherein strains are encountered in shock events, intentional or otherwise, such as powder compaction, shock welding, or insufficient momentum trapping, the associated temperature contribution must be taken into account. In fact this is a means by which heat can be added to a system and if used constructively can enhance, for example, consolidation or if sufficiently large and not desired, induce local melting in the sample.

2. Temperature Sources

Temperatures resulting from a strain free shock pressure, are attributed to the adiabatic (ΔT_A) and residual (ΔT_r) temperatures and are shown in fig. 1 for 304 stainless steel /2/.

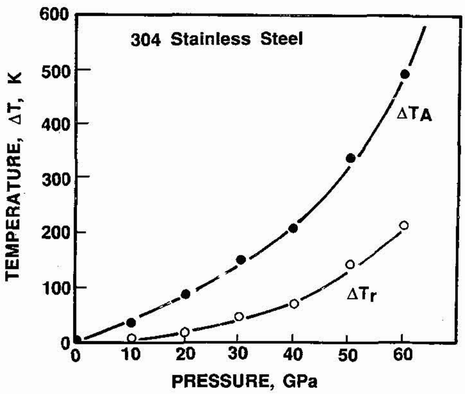

Fig. 1 Adiabatic (ΔT_A) and residual (ΔT_r) temperature rise as a function of pressure. Data from /2/.

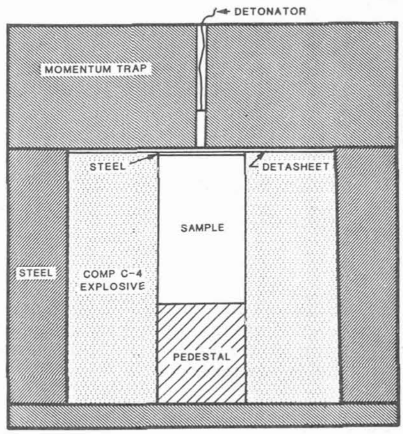

Fig. 2 Cross section schematic of the axi-symmetric shock loading assembly.

The experiments discussed here, were performed with cylindrical implosions such as that shown schematically in fig. 2. The shock conditions and sample characterization are given in /3/. The nonuniformity of the shock wave, as it converges on the central axis, poses an interpretational problem of knowing the magnitudes of the total temperature at any point within the cylindrical volume. In particular a higher pressure in the central axis region produces a higher temperature in the center than the outside diameter of the cylinder. Additionally, cylindrical implosions are not totally strain free, even though great efforts may be expended to achieve this. None-the-less, an understanding of the strain contribution in the shock characterization is necessary, particularly if larger strains are present. It is well understood that deformation produces heat within a sample being deformed, and as the deformation increases the temperature increases. Temperatures induced by strain can increase several fold over the residual temperature (ΔT_r) and result in notable temperature effects such as annealing, degradation, phase transformations, spallation susceptibility and melting /3/. Measurements on 304 stainless steel at a strain rate of 10^3/sec. showed a nonlinear increase in temperature as a function of strain, with a ΔT increase of 6 °C for a 7% strain at ambient test temperature /4,5/. For a given material, the time over which the deformation induced temperature (ΔT_ε) dissipates throughout a shocked sample, greatly depends on the sample and shock geometry, (the time for reflected tensile waves to be attenuated over specific geometric distances is of the order of µsec.). The shock conditions and sample characteristics are given in /3/. For solid cylindrical geometries the associated temperatures ΔT_A, ΔT_r, ΔT_ε and their sources are shown in Table 1. After the passage of the shock wave, the remaining temperature is composed only of ΔT_r and ΔT_ε and is shown as ΔT total. The magnitudes of ΔT total are schematically shown in fig. 3. The pressure profile vs

Table 1. Temperature functions of pressure and strain in solid cylindrical samples.

Temp.	Press.	Time	Magnitude
ΔT_A	f(P)	η–μs	f(P)
ΔT_r	f(P)	μs-min.	f(P)
ΔT_ε	f(ε)	μs-min.	f(ε)

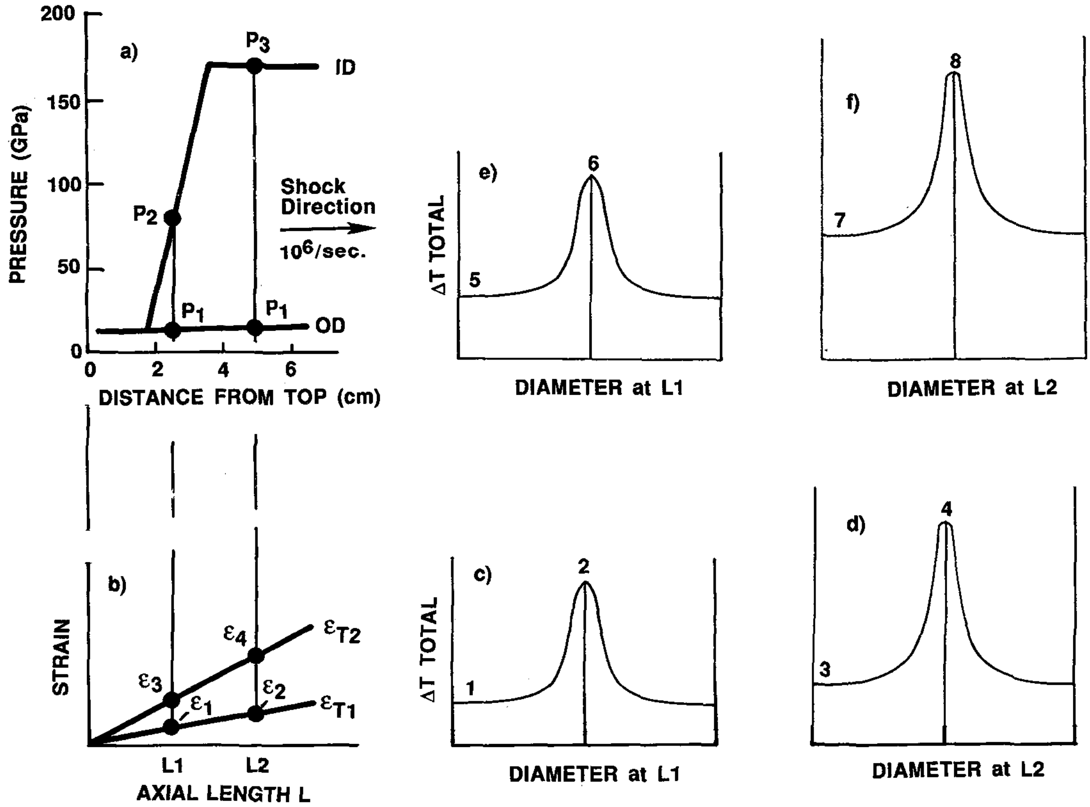

Fig. 3 Resultant temperatures derived from experimental and calculated data for 304 SS (a) pressure vs axial length L, for the outside (OD), and inside (ID) diameter, (b) strain vs axial length L, for overall strains ε_{T_1} and ε_{T_2}, (c) total ΔT rise across the diameter at axial length L1, for a strain of ε_1, (d) same as c, except at L2, and a strain of ε_2, (e) same as c, except for a strain of ε_3 and, (f) same as d, except for a strain of ε_4. In general, at any point x,
ΔT total = $\Delta T_r(P_x) + \Delta T_{\varepsilon x}$

axial length, shown in fig. 3a, are calculated values using a hydrocode calculation /6/. The points P_1 and P_2 are the pressures corresponding to the outside (OD) and inside (ID) diameter at the axial length L1. Similarly, P_1 and P_3 for the axial length L2. Strain vs axial length, shown in fig. 3b, was experimentally measured and reported earlier /7,8/. A griding technique was used to obtain the strain values ε_1-ε_4, and the overall strains ε_{T1} and ε_{T2} were obtained by variations in momentum trapping /9/. The ΔT_r and ΔT_ε contributions for specific locations L1 and L2 are shown for two overall strains, ε_{T2} and ε_{T1} (where $\varepsilon_{T2}>\varepsilon_{T1}$) for the cross sections of the cylinder at axial lengths L1 and L2. These are shown with increasing strains and pressures from 3c,d,e, and f. Thus for a given strain, i.e. ε_1, at an axial length of L1, a temperature profile across the diameter could be depicted by fig. 3c. The temperature of the sample outer diameter would be at $T_0 + \Delta T$, where ΔT is ΔT_r (as a function of P_1) plus ΔT_{ε_1} resulting from the strain value of ε_1. This is marked on fig. 3c by the number 1. The central axis would have a total ΔT derived from ΔT_r (from pressure P_2), plus ΔT_{ε_1} (from ε_1). This is marked on fig. 3c by the number 2. Similar descriptions apply to strains ε_2, ε_3, ε_4. Table 2, sums up these conditions and defines the total temperature at the axial (L1 and L2) and radial (1-8) positions within a post shocked axisymmetric cylinder experiencing strain.

Table 2. Strain-pressure-temperature sources

Total Strain	Axial Length	Radial Position	ΔT Source
ε_{T_1}	L1	1	$\Delta T_r(P_1) + \Delta T_{\varepsilon_1}$
		2	$\Delta T_r(P_2) + \Delta T_{\varepsilon_1}$
	L2	3	$\Delta T_r(P_1) + \Delta T_{\varepsilon_2}$
		4	$\Delta T_r(P_3) + \Delta T_{\varepsilon_2}$
ε_{T_2}	L1	5	$\Delta T_r(P_1) + \Delta T_{\varepsilon_3}$
		6	$\Delta T_r(P_2) + \Delta T_{\varepsilon_3}$
	L2	7	$\Delta T_r(P_1) + \Delta T_{\varepsilon_4}$
		8	$\Delta T_r(P_3) + \Delta T_{\varepsilon_4}$

As depicted in Table 1, ΔT_ε is independent of shock pressure and its magnitude is dominated by the magnitude of strain. Additionally, ΔT_r and ΔT_ε are separated in time by several μsec. (depending upon which axial position the data is taken). However, the temperature in the central axis region, due to a higher pressure there (thus a higher ΔT_r) must thermally conduct radially outward. This results in a net heat flow from the higher pressure center to the low pressure outside diameter. This has been experimentally measured and reported earlier /8/, for a 1.9 % strain ε_{T1} condition with pressures up to 1.7 Mbars.

Illustrated in fig. 4 is a schematic representation of the time-temperature history event. Upon the first impingement of a shock wave on a sample at temperature T_o, the first temperature rise above T_o is the adiabatic (ΔT_A) immediately followed by the residual (ΔT_r) temperature. The adiabatic temperature has a duration equivalent to the pulse width and in these experiments was 0.1 μsec. (100 ηsec.). Its time position at any reference point within a specimen occurs at the upper nanosecond time frame. The time position of the residual temperature occurs immediately after the shock release and remains in the sample

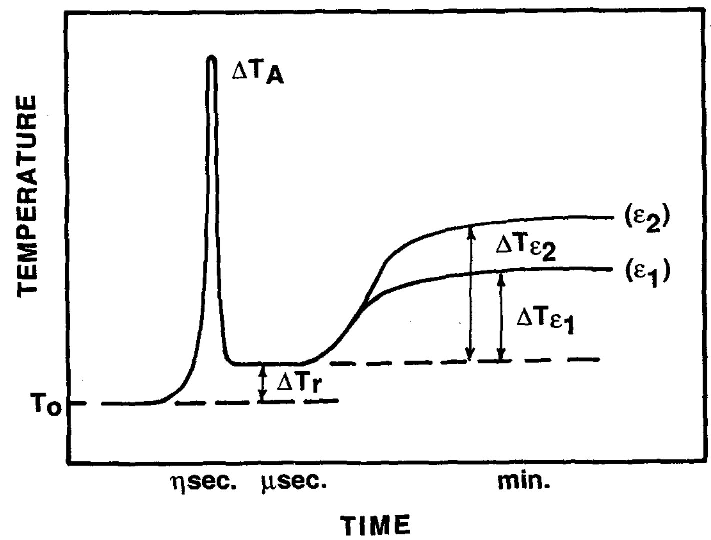

Fig. 4 Schematic of time-temperature history for a fixed pressure-strain shock event.

(till eventually cooled to the surroundings). Thus, on the time scale it is shown as fractions of μsec. to min. The strain temperature in homogeneous samples occurs only after the shock wave is reflected and traverses the sample. From a free surface at the bottom end of the axisymmetric cylinder, this time is equivalent to the sample holder length divided by the shock velocity, therefore at any point along the sample holder, the time delay from the adiabatic temperature ΔT_A to the strain induced temperature ΔT_ε, is equal to two times the axial length distance divided by the shock velocity. Different strain values depicted by ε_1 and ε_2 are represented as $\varepsilon_2 > \varepsilon_1$ resulting in increased strain temperatures. Because ΔT_ε and ΔT_r are independent of each other, one can obtain the value of ΔT_ε at equivalent pressures (constant ΔT_r), for a series of implosions made at various total strains. To date samples have been done with total strains of 1.9% and 6.7% which have had their residual temperatures measured. The temperature measurements were performed on post shocked samples, which were shocked and trapped in dry sand with a 60 to 75 second delay after the shock event. However, these measurements must be made as quickly as possible and monitored with time. A time-temperature profile, particularly for high pressure shocks (larger ΔT_r) will show a temperature increase with time, as the higher ΔT_r from the center axis diffuses out towards the outside diameter. This was shown schematically in fig. 3c-f. This technique along with calorimetry is reported in /10/ for 304 SS. The strain temperature, ΔT_ε for an overall strain of ε_{T1} (1.9%) was 4 °C above the ambient temperature (T_o = 20 °C), and remained unchanged for more than 5 min. For an overall strain of ε_{T2} (6.7%), the overall ΔT was 138 °C. The temperature-strain data are shown in fig. 5. While more data points are needed, the general shape of the curve can be established, particularly in light of the data at 10^3/sec /4/. This would allow for the ΔT_ε contribution to be known by merely measuring the total overall strain of the sample. Secondly, it is an experimental method by which ΔT_r (at zero strain) can be confirmed. At a later time (min.), additional heating due to the higher ΔT_r temperature in the central portion of the axisymmetrical cylinder, will conduct towards the surface. In this case this delayed temperature increase was 80 °C above the 138 °C initially measured temperature. This additional temperature increase is due to the shock pressure but is independent of the strain and should not be neglected.

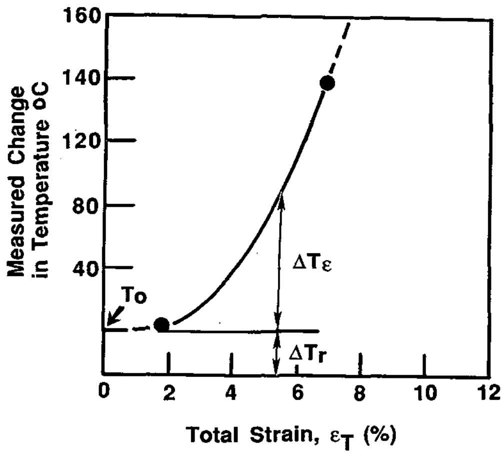

Fig. 5 Temperature vs total strain in 304 SS at equivalent pressures.

3. Summary

The present investigation discusses for axisymmetric cylinders, the interpretation of the observed "residual temperature" due to a shock implosion. The observed temperature has two components, ΔT_ε and ΔT_r. At very low strains, ΔT_ε approaches zero and the observed temperature is predominantly from ΔT_r. However, as the strain increases so do the strain temperatures ΔT_ε, which contributes to the observed temperature. A method of experimentally determining the ΔT_ε as well as the ΔT_r contribution in 304 SS were presented. This technique is equally valid for any homogeneous material undergoing similar shock conditions.

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