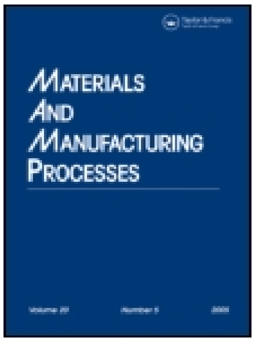

Materials and Manufacturing Processes

ISSN: 1042-6914 (Print) 1532-2475 (Online) Journal homepage: https://www.tandfonline.com/loi/lmmp20

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To cite this article: K. Srinivasan & P. Venugopal (2008) Formability Limit in Containerless (Open Die) Extrusion of Commercial Purity Titanium Rods and Tubes, Materials and Manufacturing Processes, 23:4, 347-351, DOI: 10.1080/10426910801976544

To link to this article: https://doi.org/10.1080/10426910801976544

Materials and Manufacturing Processes, 23: 347–351, 2008

ISSN: 1042-6914 print/1532-2475 online
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Formability Limit in Containerless (Open Die) Extrusion of Commercial Purity Titanium Rods and Tubes

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Containerless extrusion requires far less forces compared to conventional direct extrusion of rods and tubes due to the elimination of container wall-billet friction. But the strains that can be imparted are less in the former due to the unsupported billet which gets upset first if the axial stress exceeds yield stress of the billet material. If this stress is equal to yield stress, it corresponds to the limit of the process of pure containerless extrusion. It is found that this limit strain as predicted by theory is far less compared to what is observed experimentally. This discrepancy is explained on the basis of heating that takes place in the deformation zone due to ideal, frictional, and shear work done in carrying out the extrusion process.

Keywords Container; Die angle; Experimental; Extrusion; Friction; Limit; Punch pressure; Strain; Stress; Temperature; Theoretical.

1. INTRODUCTION

All the three principal stresses are compressive for sound extrusion and therefore the formability of a given material is more in extrusion compared to other metal forming processes [1]. But the tooling setup is complicated in conventional container extrusion (Fig. 1) compared to containerless extrusion (Fig. 2). Moreover container billet friction is eliminated [2] in the later. For rod extrusion the total force is as follows:

$$F_{TOT} = F_{ID} + F_{DFR} + F_{CWFR} + F_{SH} \text{ (Conventional)}$$
$$F_{TOT} = F_{ID} + F_{DFR} + F_{SH} \text{ (Open die).}$$

For tube extrusion mandrel billet friction has to be included. Therefore the total force will become

$$F_{TOT} = F_{ID} + F_{DFR} + F_{CWFR} + F_{MBFR} + F_{SH} \text{ (Conventional)}$$
$$F_{TOT} = F_{ID} + F_{DFR} + F_{MBFR} + F_{SH} \text{ (Open die).}$$

Because of the unsupported billet in containerless extrusion, buckling and upsetting are to be avoided. By keeping the height to diameter ratio $(h_o/d_o) < 3.0$ chances of buckling is eliminated. If the pressure required for extrusion equals the yield stress, upsetting will be dominant. The extrusion strain at which this starts happening is known as the limit strain [1, 2]. In the present work theoretical and experimental values of the limit strains are determined and the discrepancy between the two is explained for both rods and tubes of commercial purity titanium. The limit strain is the maximum strain that can be imparted in containerless extrusion in single pass. It depends on the die angle.

2. EXPERIMENTAL WORK

Commercial purity titanium rods of 40 mm diameter and 150 mm long were heavily hot forged in a double action pneumatic hammer to 28 mm diameter rods after applying a glass coating to prevent the penetration of oxygen from the atmosphere. It is then annealed at 773 K for 2 h. Compression test samples of $h_o/d_o = 1.5$ (with $d_o = 24$ mm, $h_o = 36$ mm), ring compression test samples of $OD : ID : h_o = 6{:}3{:}2$ with $h_o = 8$ mm, and extrusion test samples of $h_o/d_o = 1.5$ with $d_o = 24$ mm were machined from annealed commercial purity titanium rods and used in a 100 T hydraulic press for carrying out (i) compression tests and ring compression tests on commercial purity titanium to determine K, n, S_y, and μ and (ii) cold extrusion tests to determine experimental punch pressure. From the compression test force stroke diagram was recorded. True stress true strain diagrams were generated. Log log plot of true stress true strain was done. The value of stress at a strain value of unity gives the strength coefficient and the slope gives the strain hardening exponent. Yield stress was also determined. From the ring compression test percentage reduction in height and percentage increase in inner diameter of the ring was measured. From a standard chart [3] the friction coefficient μ was determined. Extrusions were done at four die angles and five exit diameters keeping entry diameter of the dies constant at 24 mm. Additionally for tubes a mandrel of 10 mm diameter was used. The exit diameters of the die are 19.4, 20.1, 20.9, 21.7, and 22.3 mm. The corresponding strains for rod are 0.15, 0.20, 0.28, 0.35, and 0.43 mm. The corresponding strains for tube are 0.18, 0.25, 0.35, 0.45, and 0.54 mm. A stainless steel sheathed coaxial chromel-Alumel thermocouple was

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Received March 24, 2007; Accepted August 5, 2007

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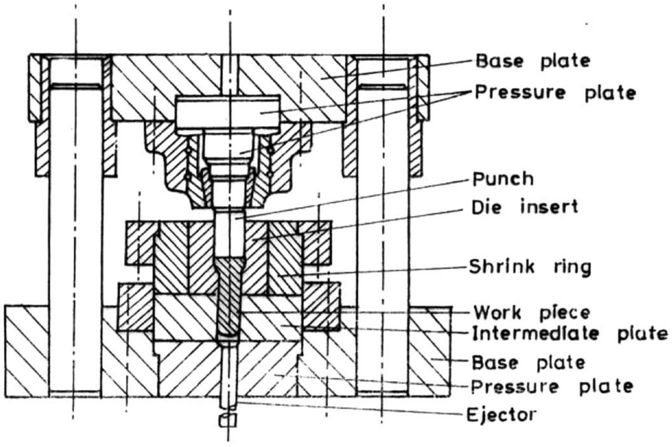


FIGURE 1.—A schematic of conventional cold extrusion (with the container).

inserted at the bottom of the billet and the temperature rise in the deformation zone was measured using a temperature recorder. Load cell was used to measure force, LVDT to measure stroke, 6 channel amplifier and X–Y recorder to amplify and record the force stroke diagrams. After the initial increase due to die filling the force remains constant. It is the proof that pure containerless (open die) extrusion had taken place. M_oS_2 was used as the lubricant [4]. All the tests were carried out at room temperature (303 K). If the force keeps on increasing it indicates that upsetting dominates. The extrusion punch pressures are calculated from the following equations [5, 6].

For rod:

$$P_{PTheo} = (\sigma_{fm})[(2\alpha/3) + (1 + (2\mu/\sin 2\alpha))\varepsilon] \tag{1}$$

$$P_{PExp} = (F_{Constant})/(A_0). \tag{2}$$

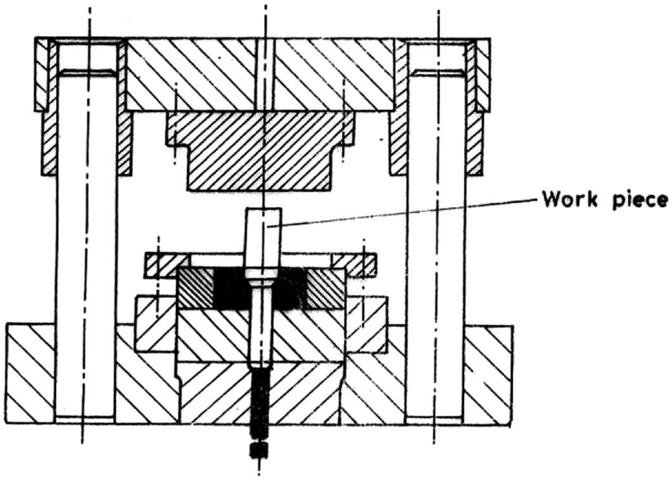


FIGURE 2.—Schematic of open die cold extrusion (without container).

TABLE 1.—Flow properties.

Material	K (MPa)	n	μ	Sy (MPa)
Commercial purity titanium	1100	0.34	0.14	390

For tube:

$$P_{PTheo} = \sigma_{fm}[(\alpha/2) + [1 + (2\mu/\sin 2\alpha) + (A_f/A_0)(\mu/\tan\alpha)]\varepsilon] \tag{3}$$

$$P_{PExp} = (F_{Constant})/(A_0). \tag{4}$$

By putting $p_p = S_y$ in Eqs. (1) and (3) and rearranging we can obtain the theoretical limit strains for rod and tube, respectively [7]:

$$\varepsilon_{L_{Rod}} = ((S_y/\sigma_{fm}) - (2\alpha/3))/[1 + (2\mu/\sin 2\alpha)] \tag{5}$$

$$\varepsilon_{L_{Tube}} = ((S_y/\sigma_{fm}) - (\alpha/2))/ \times [1 + (2\mu/\sin 2\alpha) + (A_f/A_0)(\mu/\tan\alpha)]. \tag{6}$$

3. RESULTS

The compression and ring compression test results are given in Table 1. The constitutive equation for commercial purity titanium in the present case is $\sigma = 1100(\varepsilon)^{0.34}$. Theoretical and experimental punch pressures are plotted against strain at different die angles and are shown in Figs. 3 and 4 for rod end tube. For tube the punch pressure for a strain of 0.54 is not shown at different angles. These values are very much higher than the yield stress S_y (390 Mpa). All these samples were heavily upset and no extrusion had taken place. Some values are extrapolated.

We have used a correction factor which is given by the ratio of theoretical punch pressure to experimental punch pressure. This ratio will be >1. As you go away from the optimum die angle on either side the variation of punch pressure is assumed to be symmetrical. Similarly, a correction factor for limit strains was used. It is given by the ratio of theoretical limit strain to the experimental limit strain. This ratio will be <1. The curves are assumed to be symmetrical on either side of optimum angle. Shear force directly varies with die angle. Die friction force inversely varies with angle. Mandrel friction force also inversely varies with angle. As the die angle increases F_{ID} is constant, F_{SH} increases, and F_{DFR} and F_{MBFR} decrease [8]. The dependence of individual force components on die angle is shown by the following equations.

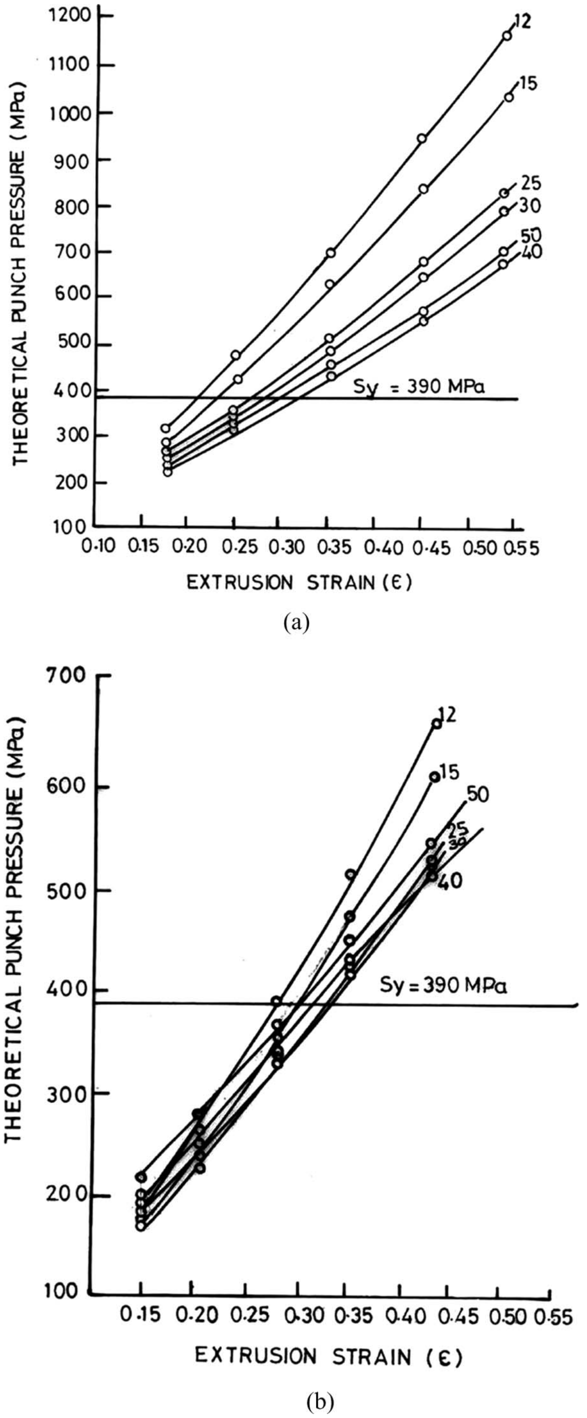
For rod:

$$\text{Shear force} = A_0\sigma_{fm}(2\alpha/3) \tag{7}$$

$$\text{Die friction force} = A_0\sigma_{fm}\varepsilon_r(2\mu/\sin 2\alpha). \tag{8}$$

For tube:

$$\text{Shear force} = A_0\sigma_{fm}(\alpha/2) \tag{9}$$



(a)

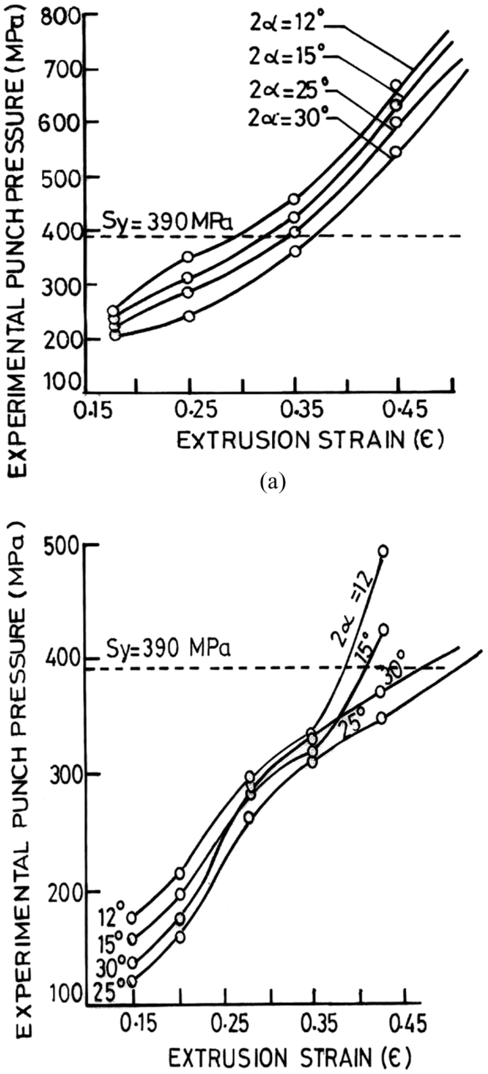
(b)

FIGURE 3.—Determination of theoretical limit strains in containerless extrusion of (a) tubes and (b) rods.

$$\text{Die friction force} = A_0 \sigma_{fm} \varepsilon_t (2\mu / \sin 2\alpha). \tag{10}$$

$$\text{Mandrel friction force} = (A_f / A_0)(\sigma_{fm}) \times (\varepsilon_t)(\mu / \tan \alpha). \tag{11}$$

Therefore, one obtains a boat curve with minimum Pp at the optimum die angle (see Figs. 5 and 6). The overall effect is that an inverted boat curve is obtained for limit strains. The strain corresponding to $Pp = S_y$ is the limit strain. The limit strains for different die angles are determined with the help of a horizontal line drawn in the figures corresponding to yield stress ($S_y = 390\,\text{MPa}$). The limit strain is plotted against die angle for rod and tube in Figs. 7 and 8. Table 2 shows the calculated temperature rise due to adiabatic heating, in the deformation zone. Frictional and shear heating are also expected to be substantial due to the low value of ρ and C and high value of σ_{fm} [9–11] for commercial purity titanium. The measured temperature in the deformation zone was found to go upto as high as 80°C.



(a)

(b)

FIGURE 4.—Determination of experimental limit strains in containerless extrusion of (a) commercial purity titanium tubes and (b) Commercial purity titanium rods.

4. DISCUSSION

As the angle increases, limit strain (S_L) increases and then decreases. It is maximum for $2\alpha = 25°$ [10, 11] for rod and $2\alpha = 40°$ for tube (extrapolated). These are the

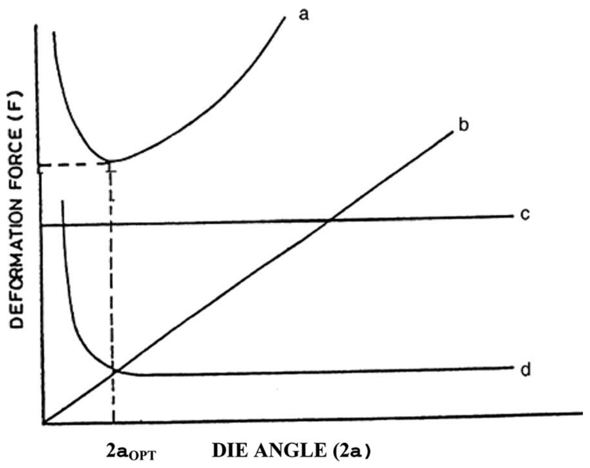


FIGURE 5.—Variation of force with die angle for a given extrusion strain in rod ODE. a – Total force; b – Shear force; c – Ideal force; d – Die frictional force.

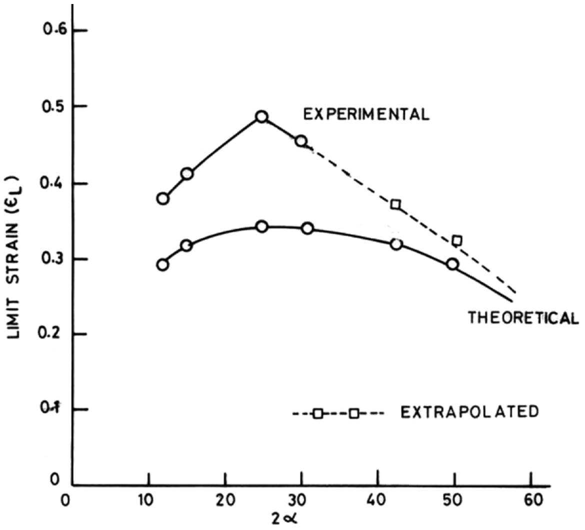


FIGURE 7.—Limit strain against die angle for rod.

optimum angles for rod and tube. Theoretical values are less compared to experimental values. It is explained on the basis of lowering of flow stress due to temperature rise in the deformation zone. It is caused by adiabatic, shear and frictional heating. It is appreciable for commercial purity titanium which has low density, low specific heat, and high flow stress. In the present case of axysymmetric extrusion, only when the axial stress is less than the yield stress pure extrusion will dominate. Otherwise upsetting will dominate. There are three compressive stresses, namely, axial stress (σ_z), radial stress (σ_r), and tangential stress (σ_t), and from yield criterion (Von Mises or Tesca) it can be shown that σ_z could be less than S_y for causing plastic deformation because of the additional presence of σ_r and σ_t in the deformation zone. The mean or hydrostatic component is more in this case. This increases ductility and delays fracture. A stress can be divided into two parts, namely, mean component and deviator component. Deviator component causes plastic deformation and shape changes while mean component causes elastic deformation and volume changes which is responsible for closure of cracks and pores [12]. Outside the deformation zone and above the die σ_z should be minimum equal to S_y to cause plastic deformation since σ_r and σ_t are zero. Limit strains are more for rod than for tube. This is due to the fact that an additional force is required due to mandrel–billet friction and consequently punch pressure will be more. Punch pressure will become equal to yields stress at lower strain itself and thus the limit is reached earlier in tube extrusion than in rod extrusion.

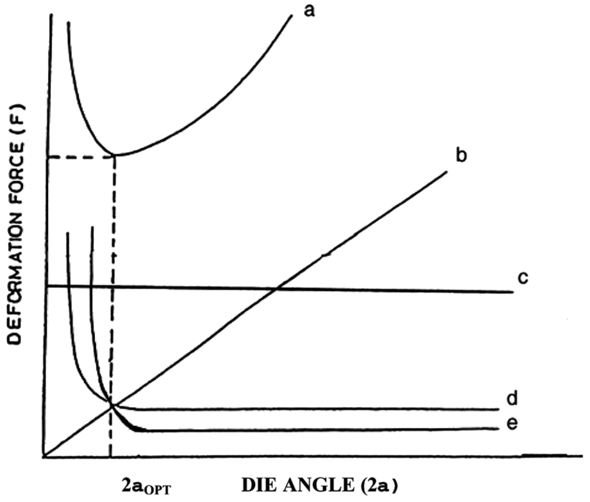


FIGURE 6.—Variation of force with die angle for a given extrusion strain in tube ODE. a – Total force; b – Shear force; c – Ideal force; d – Die frictional force; e– Mandrel billet friction force.

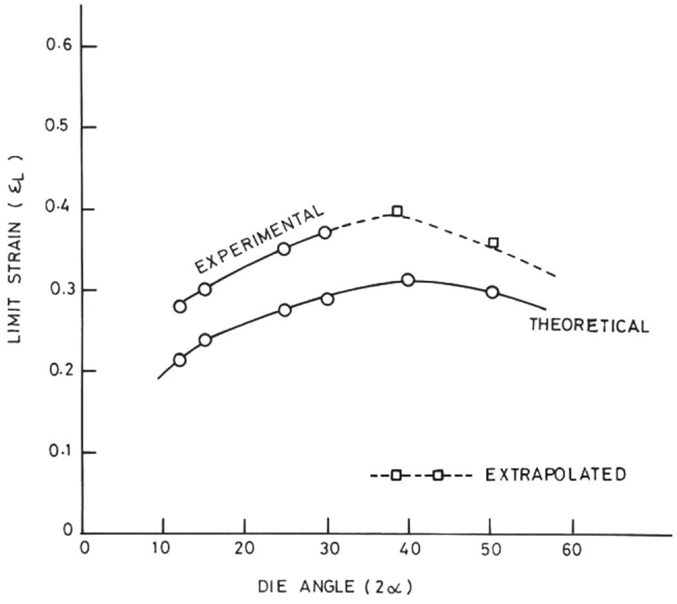


FIGURE 8.—Limit strain against die angle for tube.

TABLE 2.—Adiabatic heating.

Mean flow stress (σ_{fm}) (MPa)	Strain (ε)	(1/ρC) (KMPa)	ΔT_{Ad} K
494.7	0.21	0.42	41.4
538.8	0.28	0.42	57.4
583.1	0.35	0.42	79.8
618.3	0.42	0.42	101.3

5. CONCLUSION

Limit strains are low in containerless extrusion due to the unsupported billet and consequent danger of upsetting interfering with pure extrusion. But the temperature rise in the deformation zone due to adiabatic, shear, and frictional effects can be utilized to increase the limit strains. In fact the actual limit is very much more than that predicted by theory due to the above reason. For extrusion of commercial purity titanium, experimental limit strains are 0.48 for rod and 0.38 for tube (extrapolated), and corresponding theoretical limit strains are 0.34 and 0.31, respectively.

APPENDIX

I – Theoretical Punch Pressures Calculations

(A) For rod:

$$494.7[(2/3)(12.5)(\pi/180) + (1 + (0.28/\sin 25)(0.21)] = 253\ \text{MPa}.$$

wherein $2\alpha = 25, \varepsilon = 0.21, \mu = 0.14$, and $\sigma_{fm} = 494.7\,\text{MPa}$.

(B) For tube:

$$Pp = 51677[(15/2)(\pi/180) + ((1 + (0.28/\sin 30)0.25) + (0.25)(0.14/\tan 15)(0.78)] = 361.9\ \text{MPa}.$$

wherein $2\alpha = 30, \varepsilon = 0.25, \mu = 0.14$, and $\sigma_{fm} = 516.77\,\text{MPa}$ and $A_f/A_0 = 0.78$.

Formulas for Estimating Temperature Rise in Deformation Zone [13]–[16]

II – Formulas, Zone [13–16]

(A) Adiabatic heating:

$$\Delta T_{AD} = (\beta\cdot)(\sigma_{fm})/(\rho C).$$

(B) Frictional heating:

$$\Delta T_{Fr} = (\mu \cdot \sigma_N \cdot V_R \cos \alpha \Delta t \cdot A) \cdot (\rho C V).$$

(C) Shear heating:

$$\Delta T_{SH} = (\sigma_{fm}\alpha)/(2\rho C V)$$

where α is in radians.

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