Preliminary evaluation of hot extrusion miniaturization

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Experiments were conducted to examine the feasibility of hot extruding metals on a miniature scale thus providing a quick and cheap method of studying extrusion in general. Aluminium was successfully extruded using a new miniature hot extrusion rig, producing aluminium wires (maximum diameter 2.6 mm) as opposed to rods. A preliminary comparison of extrusion pressures on the miniature rig and on a larger extrusion press was conducted. The effects of temperature, extrusion speed and extrusion ratio on the extrusion pressure were examined for both miniature and larger scale extrusions. Extrusion speed had little effect on extrusion pressure, because the range of speeds examined was too small (due to speed limitations on the larger extrusion press). Both extrusion sizes generally displayed similar dependencies on temperature and extrusion ratio. However, the extrusion pressures for miniature extrusions were found to be always lower than for the larger scale extrusions. This may have been due the evaluation of parameters in the expression used for strain rate in the comparison. Finite element analysis may prove useful in gaining a fuller understanding of the miniaturization process.

1. Introduction
Extrusion is one of the most important hot/cold working processes in the materials industry. The extrusion of new materials and the determination of the governing extrusion processing parameters may prove a costly exercise when considering extrusion set-up time, material costs, etc. The extrusion of new materials, may also sometimes cause damage to an existing extrusion press because of excessive pressure requirements, leading to significant delays due to repair, etc.

It was the intention of the authors to develop a miniature hot extrusion rig capable of extruding small pellets as opposed to larger billets. The new rig could be used to cheaply and quickly identify the governing extrusion processing parameters prior to larger-scale extrusion. It might also be used to test the extrudability of new materials in general. Miniaturization is also a safer alternative to larger scale extrusions when extruding materials which exothermically react when they exit the die, as is the case with Hot Extrusion Reaction Synthesis (HERS) [1].

This paper examines the feasibility of hot extruding metal pellets (8.2 mm diameter, 8.2 mm long) through very small die holes (1–2.6 mm in diameter). Equivalent extrusion experiments on aluminium were conducted using the new miniature hot extrusion rig and an existing larger (5MN) extrusion press to give a preliminary indication of the relationship between the extrusion pressures.

2. Equipment and theoretical background
2.1. Equipment
The miniature extrusion rig is shown in Fig. 1. It consists of a hardened steel container with an inner shrunk fitted Inconel 718 liner, and extrudes 8.2 mm diameter pellets although different sizes can easily be accommodated. The container is heated using a Knuckel heater. The rig is fitted to a Nene tensile/compression testing machine (Fig. 1), with an extrusion ram connected to a 100 kN load cell. Hence extrusion pressures up to 1600 MPa can be achieved. The extrusion speed is obviously governed by the Nene's cross-head speed which can range from 500 mm/min to below 0.1 mm/min. Thus the miniature rig has the advantage of being able to cover a larger range of extrusion speeds than commonly found on larger scale extrusion presses. The larger extrusion press used in this work has a ram speed range between 3 and 12 mm/s.

2.2. Theoretical background
A pre-heated billet/pellet of the material to be extruded was placed in a pre-heated extrusion chamber. A slightly smaller diameter hardened steel cylinder called a 'pressure pad' was then placed behind the billet (to protect the ram from any material back extrusion). The ram was then used to push the pressure pad and billet down the extrusion chamber, forcing the material to extrude through the die hole. Only 60–70% of the height

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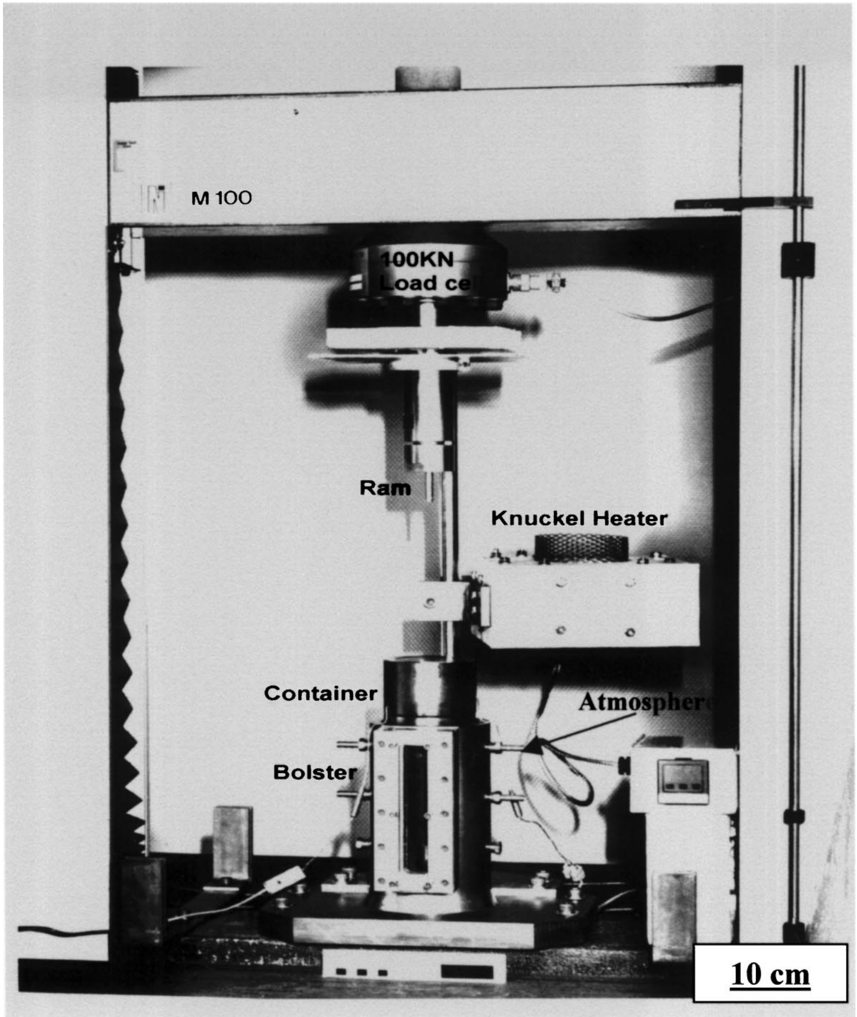

Figure 1 Miniature Hot Extrusion Rig.

of the billet is extruded through the die, leaving the rest of the billet in the form of a discard inside the container. This avoids excessive pressure build up at the die, and prevent any extrusion defects from ending up in the extruded material (extrudate). Note that when conical dies are not used, not all the material flows through the die hole. A part of the billet/pellet is stagnant and undergoes little deformation. This is known as the *Dead Metal Zone*, (Fig. 2). Since the deformation processes in extrusion are complex, the deformation is normally simplified in modelling and is assumed to occur in a truncated conical region close to the die hole, known as the *Deformation Zone*, Fig. 2. In this region the material is simply deformed and reduced in cross-section.

The force required to extrude a particular material, P_{ext} is the sum of the load required to overcome frictional forces between the billet/inner container surface, P_{f}, and the force needed for the material to extrude through the die, P_{d} (or the die force) [2]. The frictional forces between the pressure pad and the inner container wall are normally considered to be negligible and often ignored.

For extrusion through a square die, the following expression applies [4]:

$$P_{\mathrm{d}} = \sigma_0(a + b \cdot \ln R) \tag{1}$$

where σ_0 is the flow stress of material, a, b are constants, and R is the extrusion ratio (cross-sectional area of extrusion chamber/cross-sectional area of die hole).

The die force depends on the extrusion ratio, R, as well as the flow stress of the material. The latter depends on temperature and strain rate.

In reducing the inner diameter of the extrusion container (i.e., miniaturizing), it is important to take into account the change in average strain rate during extrusion. The average strain rate for extrusion is generally determined using the time for material to travel through a truncated conical volume of deformation zone. Hence, for a particular material the time average mean strain rate is related to the container size and extrusion speed through the following equation [3].

$$\dot{\varepsilon}_t = \frac{6 \cdot v \cdot D_{\mathrm{b}}^2 \cdot \ln R \cdot \tan \alpha}{D_{\mathrm{b}}^3 - D_{\mathrm{e}}^3} \tag{2}$$

where, $\dot{\varepsilon}_t$ is the time average mean strain rate, D_{b} and D_{c} are the diameters of the extrusion chamber and the extrudate respectively, v is the ram speed, and α is the semi-cone angle (see Fig. 2).

If we assume that the semi-cone angle for both size extrusions is the same, we can then use Equation 2 to arrive at an equivalent extrusion speed for the mini extrusion that would produce the same strain rate at a particular extrusion speed for the larger extrusion.

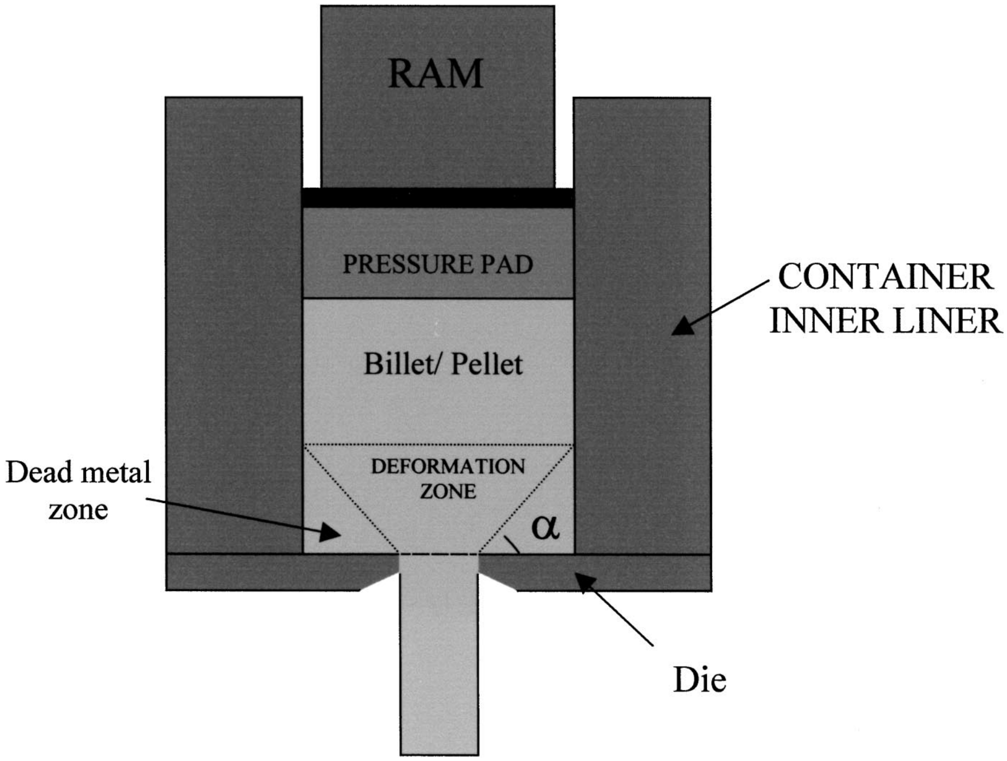

Figure 2 Schematic cross-section of extrusion chamber/billet/die arrangement.

3. Experimental

The experiments were conducted with the aim of achieving the same processing conditions for both extrusion sizes. Aluminium powder ($<45\,\mu$m, purity 99.7%)† was used for the investigation. The pellets and billets were produced by uni-axially pressing 1.2 and 458 g respectively of aluminium powder to a pressure of 205 MPa. Green densities for both pellets and billets were both approximately 88% of the theoretical density (2.7 gm/cm^3). The original masses of the pellets and billets were chosen so that immediately prior to extrusion (after upsetting) the pellet would have diameter and height of 8.2 mm (i.e., aspect ratio = 1). Similarly, the billet will have a diameter and height of 60 mm (aspect ratio = 1).

The pressure pad, billet/pellet and container were all kept at the same temperature during extrusion. The die for the larger scale extrusion was heated to a temperature 15 °C lower than the extrusion temperature. This was carried out to reproduce the same container and die temperatures obtained in the miniature extrusion rig. The billet/pellet, container and die were all lubricated using Dag 1559‡.

The extrusion speeds were chosen to achieve the same strain rate in the large and miniature extrusions. Table I shows the extrusion conditions investigated. The conditions displayed in Table I were examined in all their combinations for both extrusion sizes. Hence for a temperature of 250 °C, extrusions were carried out at extrusion ratios of 10, 18 and 32 : 1 for the two different speeds. Similarly for the 200 and 300 °C extrusion temperatures.

† AIPOCO, West Midlands, England, UK.
‡ Acheson Colloids Company, Plymouth, UK.

TABLE I Extrusion conditions examined

Temperature (°C)	200	250	300
Extrusion ratio, *R*	10 : 1	18 : 1	32 : 1
Speed (mm/s)	3, (0.41)		12, (1.64)

( ) Equivalent extrusion speed on the miniature extrusion rig to produce the same time mean strain rate on the large extrusion press.

Micro-hardness measurements (using a pyramidal diamond indenter) were conducted on the central cross-section of the extrudates for both miniature and larger extrusions. A 200 g indentation load was used for the experiments. These measurements were conducted to determine if the relative flow stresses are similar for both extrusion sizes.

4. Results

Aluminium pellets were successfully extruded using the miniature hot extrusion rig. Fig. 3 shows the difference in sizes of aluminium extrudates from the miniature and larger scale extrusions extruded at the same extrusion ratio of 10 : 1.

Fig. 4a and b, show typical extrusion load vs. ram displacement plots for the miniature and larger scale extrusion. Fig. 4a shows that the load displacement relationship for the miniature extrusion is not as smooth as that for the larger extrusion. This is believed to be due to sticking of the aluminium to the steel surface as it exits the die hole. This is increased by the higher surface area to volume ratio of the miniature extrusions. The fact that aluminium tends to stick to steel during extrusion is well documented [5]. It should be noted that experiments with other materials (lead, mixtures of nickel and aluminium powder and mixtures of titanium and aluminium powder) has produced very smooth load curves using the miniature rig. The average extrusion

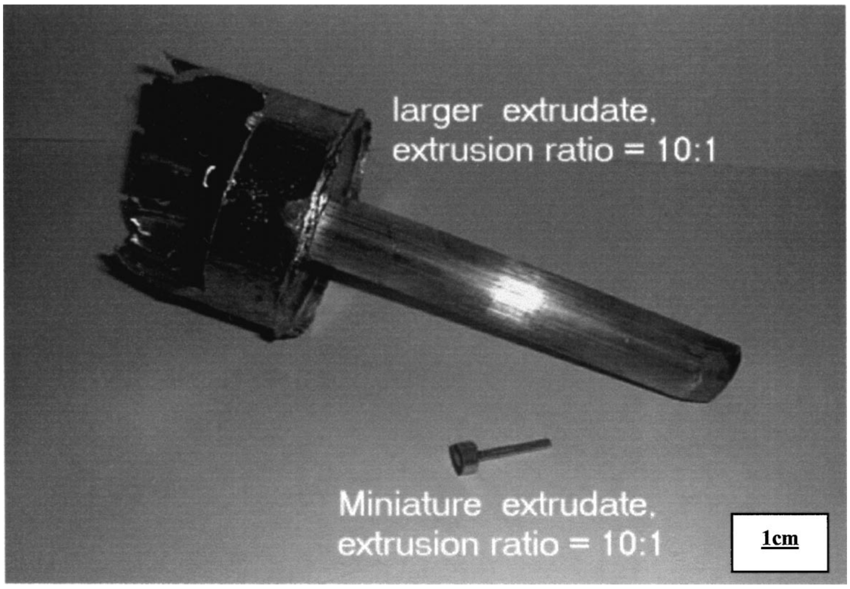

Figure 3 Miniature and larger extrudates extruded under exactly the same conditions.

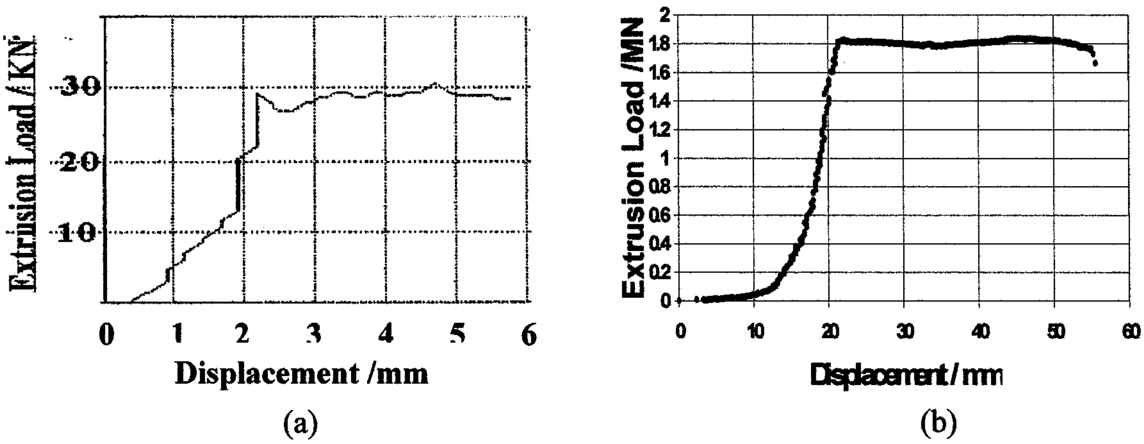

Figure 4 Extrusion load vs. displacement curves from the miniature (a) and larger scale (b) extrusions at a container temperature of 250 °C, $R = 32 : 1$ and speed 0.41 and 3 mm/s respectively.

load from each curve was calculated by simply averaging 10 equally spaced load reading during extrusion. The reproducibility of the results from the rig was measured by averaging 5 extrusions with the same extrusion conditions. The load was found to be reproducible to within ±10%. This value is consistent with the reproducibility of the larger extrusion press. All loads were converted to extrusion pressures by dividing the extrusion loads by the container cross-sectional area.

The average extrusion pressures for different extrusion temperatures, extrusion ratios and speeds were plotted for both rigs. Figs 5–7 show extrusion pressure vs. $\ln(R)$ for both extrusion presses at 200, 250 and 300 °C respectively.

The extrusion pressure was found to generally decrease with decrease in extrusion ratio and increase in temperature. Speed did not have a pronounced effect on the extrusion pressures.

The micro-hardness results for pellets and billets extruded at 250 °C and extrusion speed 3 mm/s (0.41 mm/s) using $R = 10:1$ and $32:1$ are given in Table II. Each of these values is an average of ten readings, the standard deviation is given between brackets.

TABLE II Micro-hardness measurements

Extrusion size	Micro-hardness/VHN
Larger extrusion, $R = 10:1$	41.5 (±3.0)
Larger extrusion, $R = 32:1$	42.8 (±0.4)
Miniature extrusion, $R = 10:1$	45.1 (±1.6)
Miniature extrusion, $R = 32:1$	42.0 (±4.6)

5. Discussion

It is encouraging to find that hot extrusion of metals can be conducted on such a small scale. This is a positive step forward in the miniaturization of the extrusion process. The results show that the extrusion pressure for both the miniature and larger extrusions generally increase in proportion to $\ln(R)$ in line with the relation shown in Equation 1. As the temperature is increased the material becomes softer (i.e., the flow stress decreases) and lower extrusion pressures are required. The effect of extrusion speed was not very pronounced however we only investigated two speeds with the highest speed only four times greater than the lowest. Ideally it would have been more appropriate to use variations

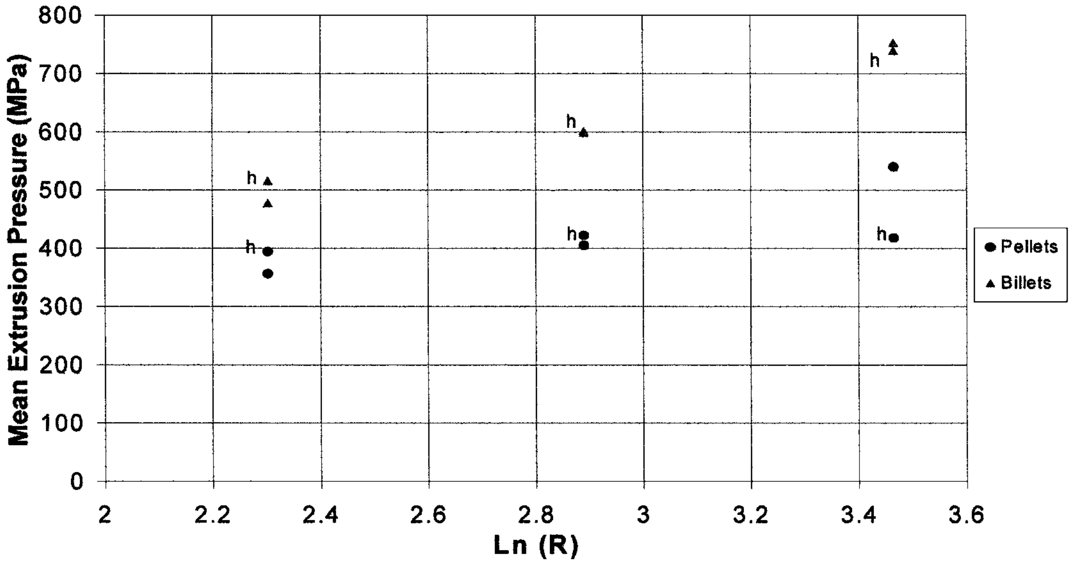

Figure 5 Effect of extrusion ratio (R) on extrusion pressure for the miniature and the larger-scale hot extrusion presses at 200 °C.

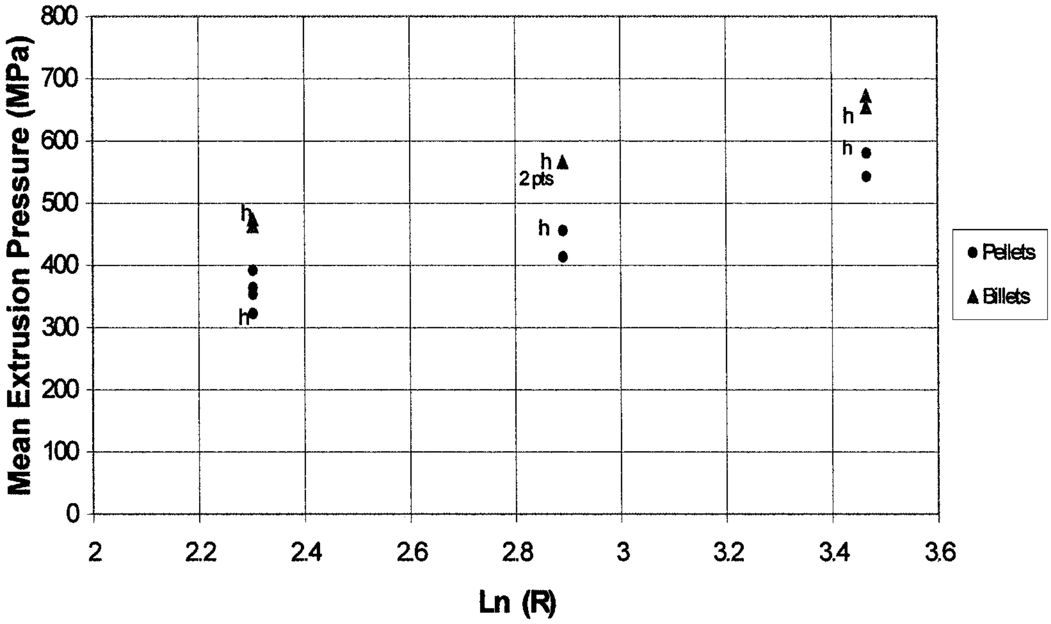

Figure 6 Effect of extrusion ratio (R) on extrusion pressure for the miniature and the larger-scale hot extrusion presses at 250 °C.

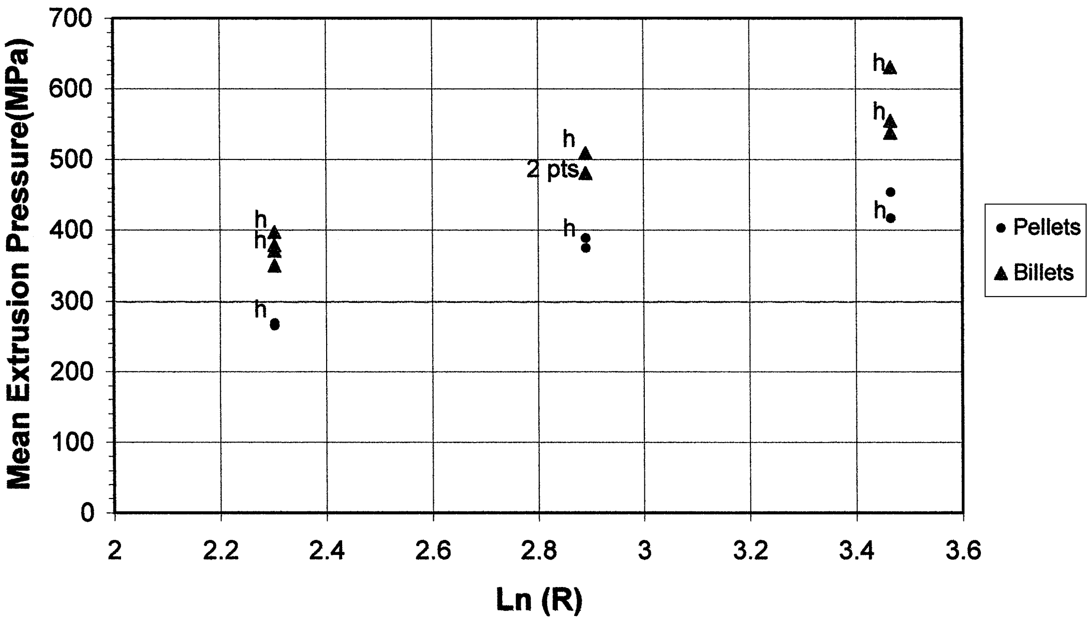

Figure 7 Effect of extrusion ratio (R) on extrusion pressure for the miniature and the larger-scale hot extrusion presses at 300 °C.

in speed over several orders of magnitude. Although it would have been possible to examine this range of speeds on the miniature extrusion rig, we were restricted by the capabilities of the larger extrusion press (the range of the larger extrusion press is 3–12 mm/s). The limit of reproducibility of the extrusion process masked any effect extrusion speed may have had. The surprising finding, is that the extrusion pressures for the miniature extrusions were *on average* ∼25% lower than those for the larger extrusions. This can be seen in Figs 4–6. The load calibration for both setups was checked and found to be correct and hence did not cause the load discrepancy. It is important to state that due to the size reduction from a 60 mm diameter (60 mm long) billet to an 8.2 mm diameter (8.2 mm long) pellet, the surface area to volume ratio is increased from 100 to 732 m^{-1}. This should have a considerable impact on the heat losses during extrusion. It is commonly accepted that at least 90% of the deformation in the extrusion process is converted into heat energy which for both extrusion sizes at conditions 250 °C, $R = 10$ is ∼300 MJ/m^3. This heat raises the temperature of the extruding material by approximately 120 °C. However, it is expected that the miniature extrusion with the higher surface area to volume ratio would lose more of that extra energy and the extruding material is expected to be at a lower temperature than the larger scale extrusion. Effectively we still need to determine how much of an effect this may be. However, the increased surface area to volume ratio for the miniature extrusion should favour higher flow stresses and essentially higher extrusion pressures for the miniature extrusions. As stated, this is the opposite of what the results show. The micro-hardness values given in Table II, for both extrusion sizes are similar. This suggests that the miniature extrusions are not noticeably softer than the larger extrusions. The question must be asked as to why they are extruding under lower pressures.

The assumption made in Equation 2, was that the semi-cone angle for both extrusion sizes is the same (and usually taken to be 45°). This angle is normally very difficult to measure in practice. If however, the miniature extrusions had a lower semi-cone angle than the larger extrusions, then this would explain the findings. A lower semi-cone angle would result in a lower strain rate (see Equation 2) at a particular extrusion speed. This would favour lower extrusion pressures. However, as mentioned this is not an easy parameter to measure. Using Equation 2, it can be seen that for the same extrusion speed and extrusion ratio, the strain rate can be increased by an order of magnitude if the semi-cone angle was increased from 15° to 70°. It is intended in future work to measure the semi-cone angle using tape cast specimens. These experiments will be the subject of further work together with a detailed theoretical study using finite element analysis of the extrusion process, to include the effect of heat transfer during the extrusion process for both miniature and larger scale extrusions.

6. Conclusions

This paper represents a first step in evaluating the feasibility of hot extruding metals on a miniature scale. This can provide a quick and economical method for studying extrusion in general.

1. Aluminium pellets each weighing less than 2 grams have been successfully hot extruded into wires (1–2.6 mm) in diameter.
2. The extrusion pressures required to extrude the same material at different temperatures and extrusion ratios generally showed similar dependencies on temperature and extrusion ratios for both the miniature and larger scale extrusions.
3. Extrusion speed had little effect on extrusion pressure.
4. The extrusion pressures for the miniature extrusions were always lower than for the larger scale extrusions. This was attributed to an assumption made regarding the semi-cone angle.
5. It is believed that an attempt can be made to measure the semi-cone angle by using tape cast specimens.
6. Since wires are produced by miniaturization, the process may also provide an alternative to 'wire drawing', when automated.

References

1. K. MORSI, H. MCSHANE and M. MCLEAN, *Scr. Mater.* **37**(11) (1997) 1839–1842.
2. V. DEPIERRE, Trans. ASME, *J. Lubr. Technol.* **92** (1970) 398–405.
3. G. E. DIETER, "Mechanical Metallurgy" (McGraw Hill, 1988) p. 628.
4. H. KUDO, *Int. J. Mech. Sci.* **2** (1960) 102.
5. C. E. PEARSON and R. N. PARKINS, "The Extrusion of Metals" (Chapman & Hall, London, 1960) p. 199.

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