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GEOMETRY FACTOR AND REDUNDANCY EFFECTS IN EXTRUSION OF ROD

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Industrial Summary

The problem of relating effects of redundancy, or unnecessary macroshearing, to the geometry of the forming pass has been investigated for a number of metal-forming operations. Relatively simple expressions linking redundancy to geometry, via the relevant geometry factors, have been established for the drawing of rod and wire, among other processes. Because of the basic geometrical similarity with the extrusion of rod, these functional relationships are often used directly in this operation to predict the response of the material to changing pass design. The validity of this approach has become questionable in view of experimental and theoretical work undertaken recently. The present paper indicates that redundant shearing strains depend on the homogeneous strain rate and in consequence of that, a unique equation relating redundancy to geometry factors, otherwise applicable to drawing, may not be sufficient in the case of extrusion. To obtain a valid assessment of the level and pattern of redundant shears, it becomes necessary to consider the strain rate distribution in the processed material.

Notation

C_1, C_2	Material constants
D_o	Initial rod diameter
D_f	Final rod diameter
t	Time
V_o	Constant ram speed
x	Horizontal distance
α	Die semi-angle
$\dot{\epsilon}$	rate
Δ	Geometry factor
ϕ	Redundancy factor

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1. Introduction

The prediction of the incidence, pattern and level of redundant deformation has exercised the attention of many researchers for considerable time. The two basic parameters associated with this type of investigation are the redundancy and geometry factors. The development of a functional relationship between the two, in any given process, makes it possible to predict, a priori, the likely response of the material, since the geometry and therefore both the pattern of flow and constraints imposed by the tools are defined by the geometry factor.

An approach of this type, to making an estimate of the efficiency of the process and the quality of the final product, is based on a tacit assumption that the level of redundancy is governed only by the pass geometry.

In those processes in which the rate of homogeneous strain is either relatively low or remains sensibly constant across the section, as for instance in drawing, the single redundancy–geometry relationship is sufficient to enable an accurate prediction to be made. This has been illustrated in the case of drawing [1–3], rotary operations [2,4] and, to a limited extent, in tube extrusion [5]. However, although from the geometrical point of view the process of rod extrusion appears to be identical to that of rod drawing, the use of the relatively simple relationships devised for the latter may not be appropriate: this is because of some basic differences in the character and mechanisms of extrusion, as compared with drawing. For instance, the drawing process involves the use of smaller die angles and deformations than is customary in extrusion, the levels of shearing strains and general inhomogeneity are higher in extrusion and the process is normally a cold-working operation, whereas in many cases extrusion is conducted at elevated temperatures. These differences will affect not only the incidence of redundancy, but also its level and pattern, as a result of the induced differentiality in the rate of flow across any given direction. This in turn, would indicate that the normal redundancy/geometry relationship may well be insufficient to define accurately the flow of the metal.

The reliability of the use of the geometry factor — devised for the drawing process — in the extrusion of rod is investigated using wax as the model material. Fully detailed information about the latter technique is provided in Ref. [6].

2. Theoretical and experimental background

The assessment of redundancy of the process is usually made by considering the value of the strain redundancy factor ϕ defined [2] as:

$$\phi = C_1 + \Delta C_2 \tag{1}$$

where, for conical dies

$$\Delta = \frac{D_o + D_f}{D_o - D_f} \sin \alpha \tag{2}$$

Since neither of these relationships necessarily reflects the effect of strain rate (although this could be incorporated for a given value in one of the constants) its magnitude must be estimated separately.

For a solid bar or rod of circular cross-section, the strain rate is given [2] by

$$\dot{\epsilon} = \frac{4V_o D_o^2 \tan \alpha}{(D_o - 2x \tan \alpha)^3} \tag{3}$$

Since most of the industrial operations of this type are carried out in straight conical dies, the present investigation is essentially orientated in that direction, but the effect of strain rate in curved dies is also indicated.

There are two possible solutions to the problem of die design in a broadly based investigation. The design can either be rationalised by assuming a specific flow characteristic or it can be directed simply at a randomly chosen flow pattern. Both of these possibilities are explored here.

In the latter case, industrial type simple conical dies are used [7], whilst in the former, CRHS (constant ratio of homogeneous strain) concept dies [2] are employed.

The well known CRHS concept is defined by the following relationship

$$Z_n / Z_{n-1} = Z^{s(n-1)} \tag{4}$$

where the function Z, referred to any section n of the pass, is in turn defined by

$$\epsilon_n = \ln Z_n \tag{5}$$

The value of the constant s reflects the rate of deformation (not the strain rate). If $s = 1$ the rate is uniform (U), if $s < 1$, the rate is decelerated (D), and an accelerated flow occurs for $s > 1$.

The uniform rate U dies approximate closely to the industrial conical tools. The basic difference between the two types lies in that the latter cannot guarantee constancy of the rate of deformation and are therefore likely to introduce some degree of variation of flow in the pass.

In all of the cases considered here, the instantaneous and mean strain rates of the operation vary along the pass, with the instantaneous rate being given by

$$\dot{\epsilon} = \mathrm{d}\epsilon / \mathrm{d}t \tag{6}$$

and the mean rate being defined by eqn. (3). These variations will affect the degree of redundant shearing and consequently the relationship between ϕ and Δ.

3. Experimental details

The following die sets were used:

Set I was designed to give a constant extrusion ratio ER of 7.11. The associated die semi-angles were 11.25 22.5, 33.75 and 45°. The die overall lengths

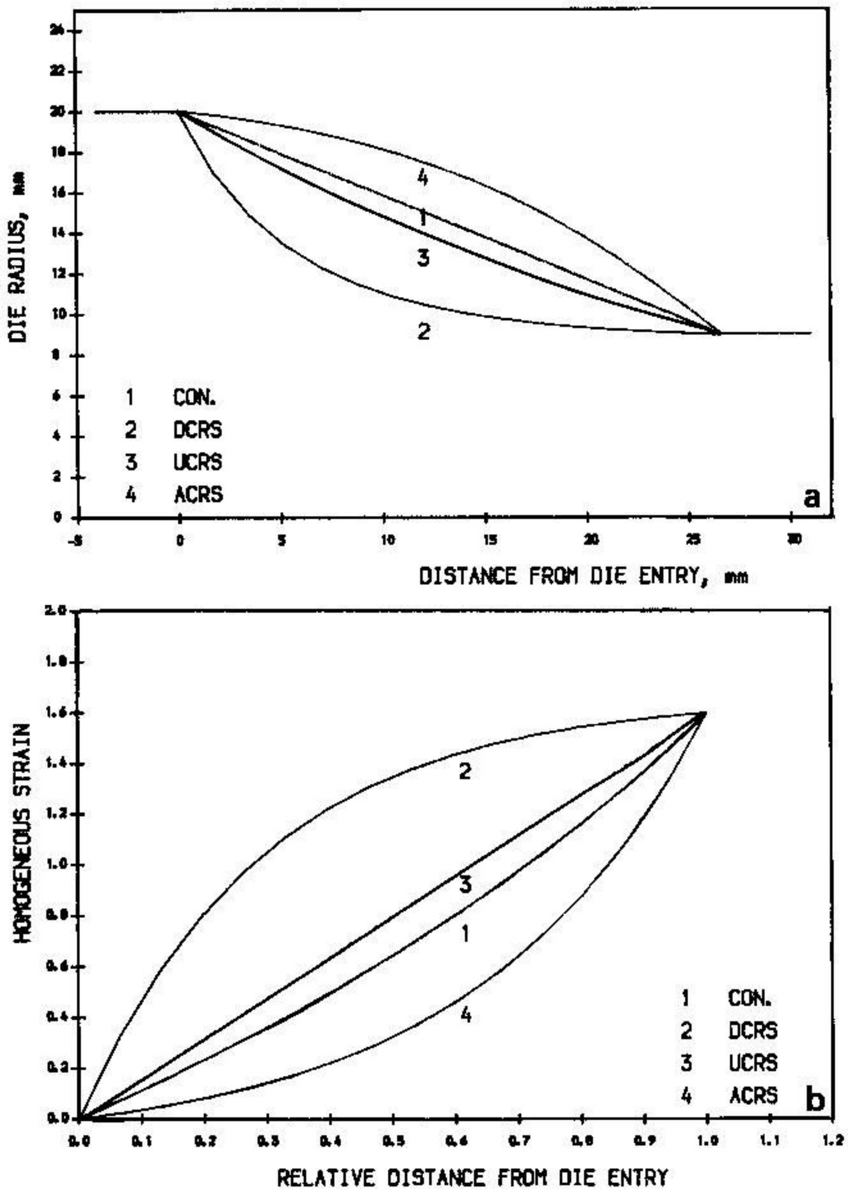

Fig. 1. Basic characteristics of conical and CRHS dies: (a) die profile; (b) homogeneous strain. (Ram velocity 1 mm/s).

were 62 mm, the respective lengths of the working zone of the pass being 61.6, 29.6, 21.2, 18.3 and 12.2 mm. These dies were used to study the effect of die angle on redundancy.

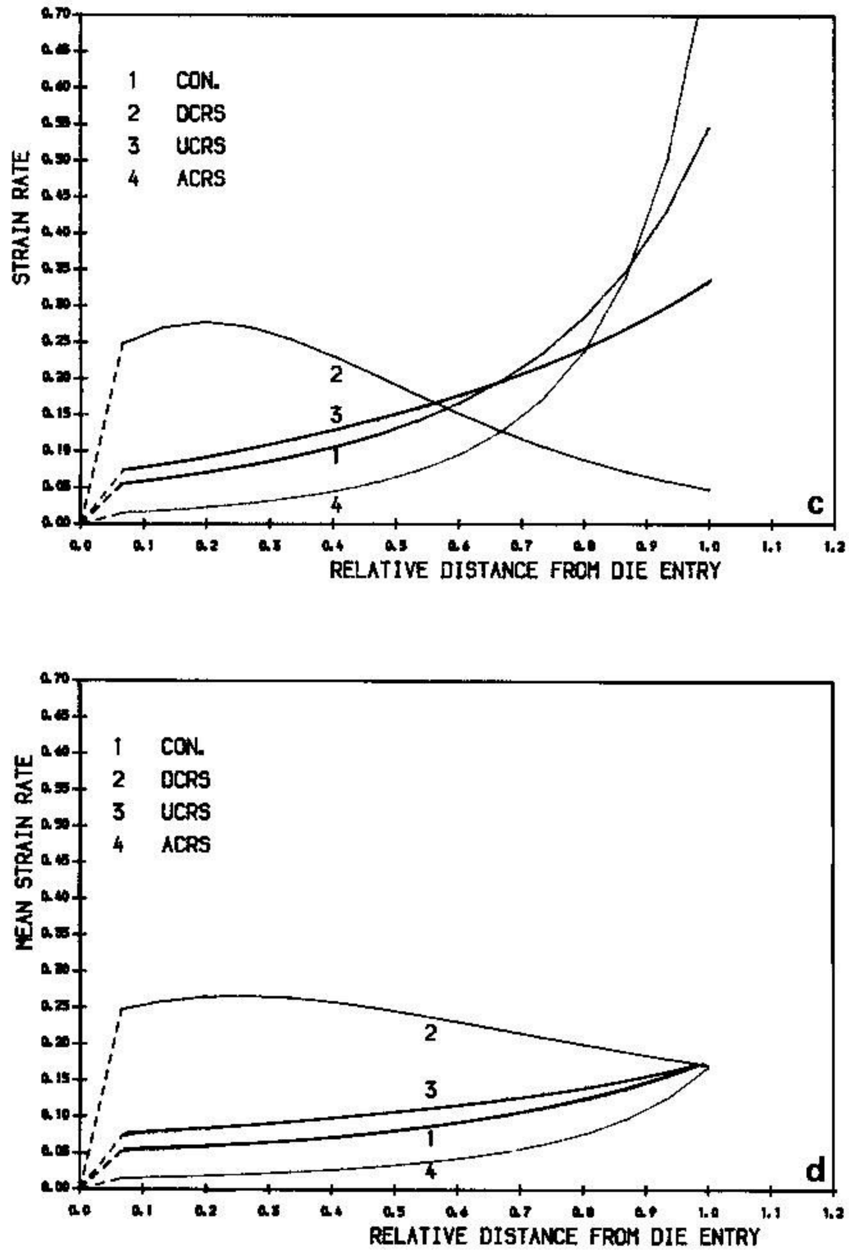

Fig. 1. Basic characteristics of conical and CRHS dies: (c) strain rate; (d) mean strain rate. (Ram velocity 1 mm/s)

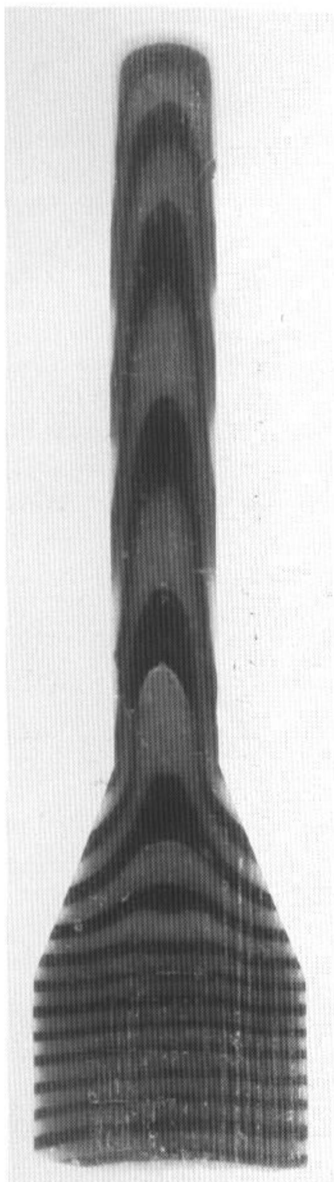

Fig. 2. A section through a typical wax billet.

Set II was designed with a view to studying the effect of ER on redudancy. The selected values of ER were 7.11, 4.94, 3.63, 2.77 and 2.19 (corresponding to die exit diameters of 15, 18, 21, 24 and 27 mm) and the constant die semi-angle was 22.5°.

Three dies based on the CRHS design concept were used. The uniform rate of deformation ($s=1$) die was designated UCRS, the decelerated rate die DCRS ($s=0.8$) and the accelerated rate tool ACRS ($s=1.2$). To introduce a measure of direct comparability with the conical (CON) dies, the die lengths of the CRHS tools were made equal to that of the 22.5° die, producing ER=4.94. In each case, the deformation zone of the pass amounted to 26.5 mm. The basic geometrical and performance characteristics of the tools used are compared in Fig. 1.

Wax billets with coloured inserts were extruded [5,6] to enable assessments of redundant longitudinal shearing strains to be made.

The constants C_1 and C_2 in eqn. (1) reflect the response of the material to macroshearing which, in turn, is affected by the rate of deformation. Whereas the variation in the respective values of the constants may not be significantly high in metallic materials, non-metallic substances, and waxes in particular [6], are highly susceptible. Typical values of those constants for the wax mixture used were established experimentally and provided the following sets of equations relating the redundancy and geometry factors

$$\text{A-rate:} \quad \phi=0.99+0.27\Delta \tag{1a}$$

$$\text{U-rate:} \quad \phi=0.99+0.115\Delta \tag{1b}$$

$$\text{D-rate:} \quad \phi=0.99+0.050\Delta \tag{1c}$$

A typical extruded and sectioned billet is shown in Fig. 2.

The "smooth" curves referring to the experimental results and plotted in Figs. 5, 7 and 9 are the "best" fits through the points.

4. Process parameters and geometry factor

The relationship between the geometry factor and characteristic features of the operation is indicated in Fig. 3 for the conical dies.

In these tools, Δ decreases sharply when extrusion ratios are small (Fig. 3(a)) and then for a given die angle tends to a constant value as ER increases. It would appear therefore that in any specific die geometry — and particularly so when small angled dies are used — Δ may lose its physical significance in assessing the redundancy factor for extrusion ratios in excess of about three.

The contribution of friction to redundancy is indicated in Fig. 3(b). This

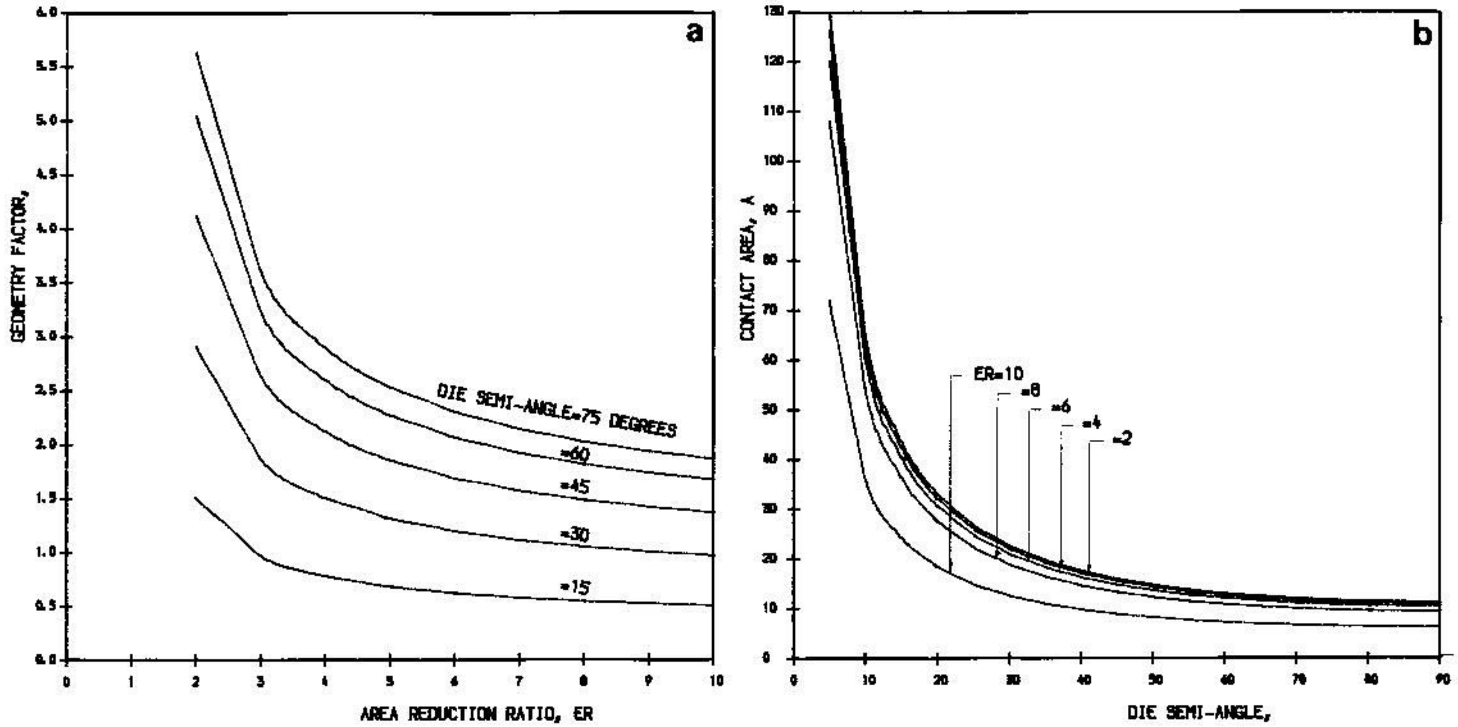

Fig. 3. Conical die properties: (a) variation of geometry factor Δ with reduction ratio ER; (b) variation of contact area with die semi-angle (A in cm^2, α°).

shows that the area of contact between the die and the processed material varies sharply within the range of small die angles, but, again tends to a constant — for the given ER— value above about 30°. Since the area of contact for extrusion ratios less than eight remains practically constant for die angles in excess of about 30°, the contribution of friction to the total redundancy of the system is likely to be very small. This is, of course, borne out by the well established experimentally, and often published, relationships between the die angle and pressure parameters in general extrusion and drawing experimentation on both solid and hollow components [1–4,8,9].

Assessments of the development and variation of the longitudinal shearing strain (the only redundant strain effect in this operation) and the associated redundancy factor, based on the experimental evidence, are given in Figs. 4 and 5 for die Sets I and II respectively. These effects are related directly to the geometry though the media of die angle and Δ (eqn. (2)), and to the mean and instantaneous strain rates.

In all of these experiments a constant ram speed of 1 mm/s was used. The longitudinal shear strain and the instantaneous strain rate represent the total, respective, quantities assessed for the whole of the extrudate and referred, where appropriate, to the specific die angle.

Considering redundancy factor ϕ (eqns. (1a)–(1c)) in relation to Δ, it is seen that the respective relationships produced by Sets I and II differ substantially in character. In Set I (Fig. 4), a rough approximation may validate the assumption of linearity, implicit in eqn. (1) However, the corresponding curve of Fig. 5 (Set II) is hyperbolic in shape and approaches a constant value only for higher extrusion ratios. The applicability of the linear equation to this case is therefore in doubt. The discrepancy arises partly as a result of the adopted deficiencies of Δ and partly from the fact that eqn. (1) is usually quoted in its simplified, approximate form. In reality, an equation correlating the influence of the die angle in the total against homogeneous strain relationship contains a square term normally neglected because of its numerical insignificance [1]. In specific cases, the numerical value can be significant. The "square" term results from the standard mathematical derivation of a general equation that links a family of parallel straight lines.

In both Sets, ϕ and Δ are shown to be dependent on the strain rate, as well as on the die geometry.

A further consideration of Fig. 3 supports the view that the geometry factor increases with α (for a constant ER) and that it decreases with increasing ER for a constant value of α. The variation of redundancy cannot therefore be defined uniquely by the simplified eqn. (1). An additional parameter enters into consideration and as Figs. 4 and 5 indicate, the strain rate is the contributory element.

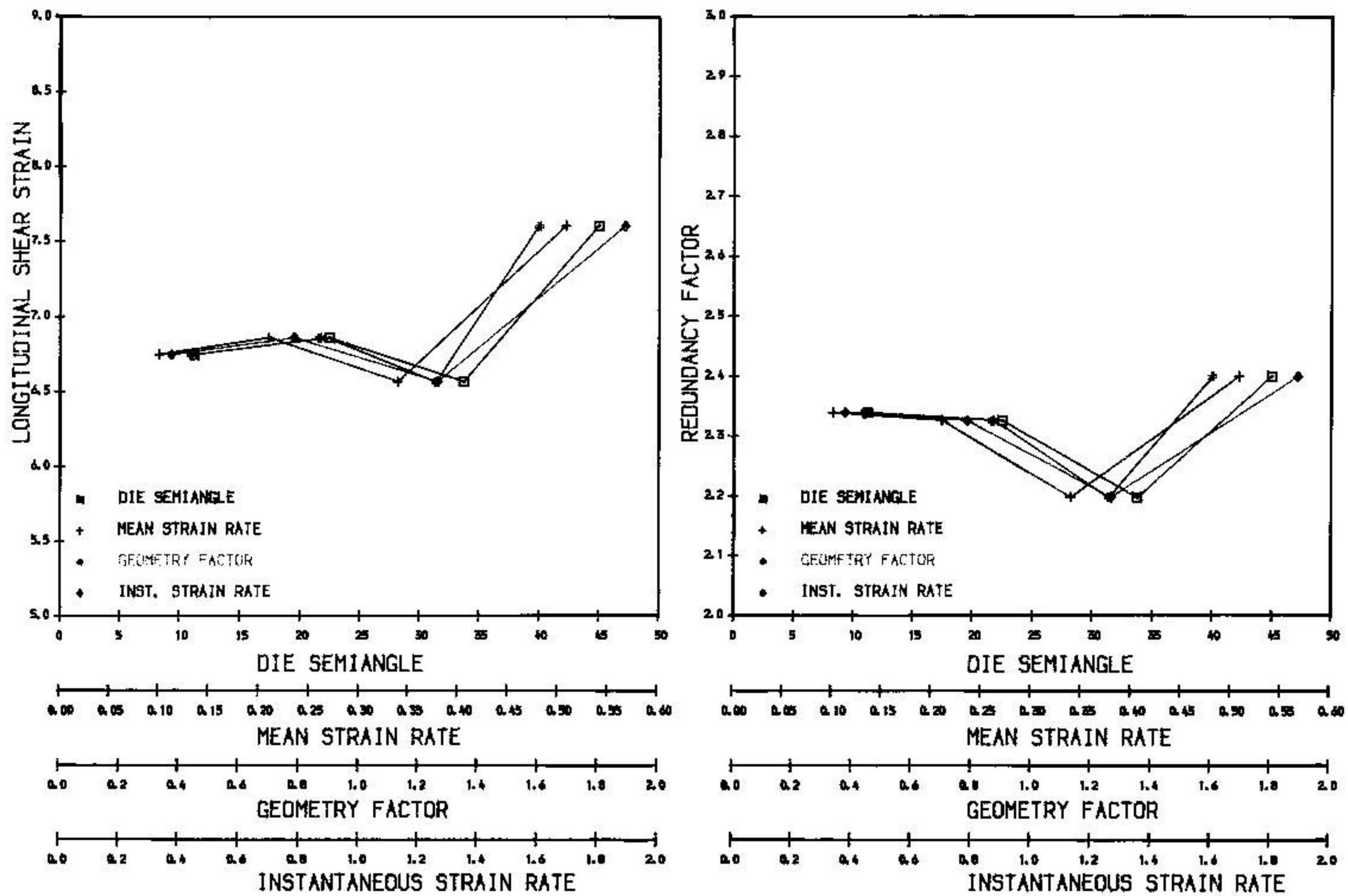

Fig. 4. Conical die properties — Set I: Variations of the longitudinal redundant shearing strain and redundancy factor ϕ with die semi angle and strain rates.

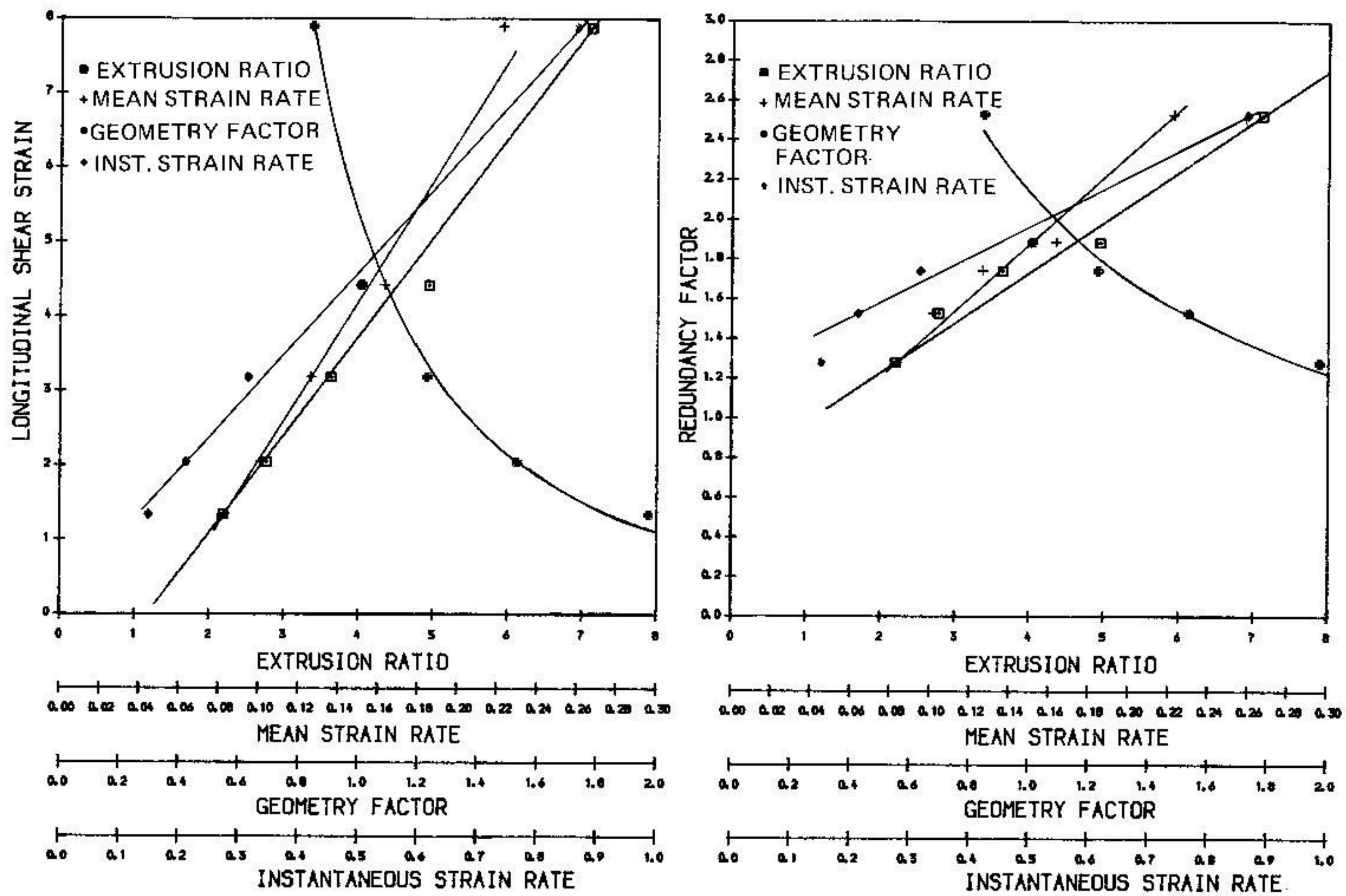

Fig. 5. Conical die properties — Set II: Variations of the longitudinal redundant shearing strain and redundancy factor ϕ with extrusion ratio ER and strain rates.

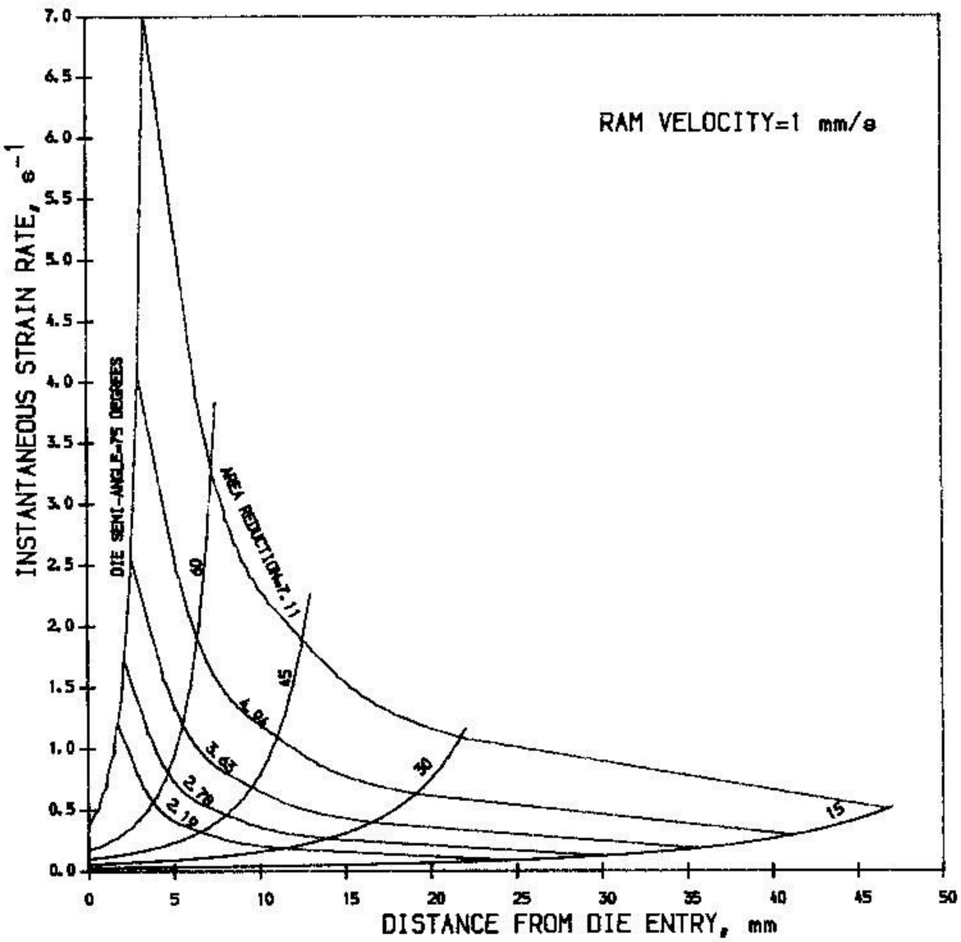

Fig. 6. Dependence of strain rate on α and ER.

5. The effect of strain rate

The basic dependence of the strain rate on the die angle and its development along the pass for a given value of ER are shown in Fig. 6, which was obtained for $D_0 = 40$ mm and $V_0 = 1$ mm/s.

At the entrance to the die, the instantaneous strain rate begins to increase rapidly; the increase being exponential. For a given ER, the strain rate is higher for larger die angles although the actual die length is reduced. A variation along the pass is clearly established.

A similar trend is observed in the conical dies regarding the incidence and pattern of the longitudinal shearing strain. The relevant plots in die Set II are shown in Fig.7 and indicate an exponential type of relationship between the

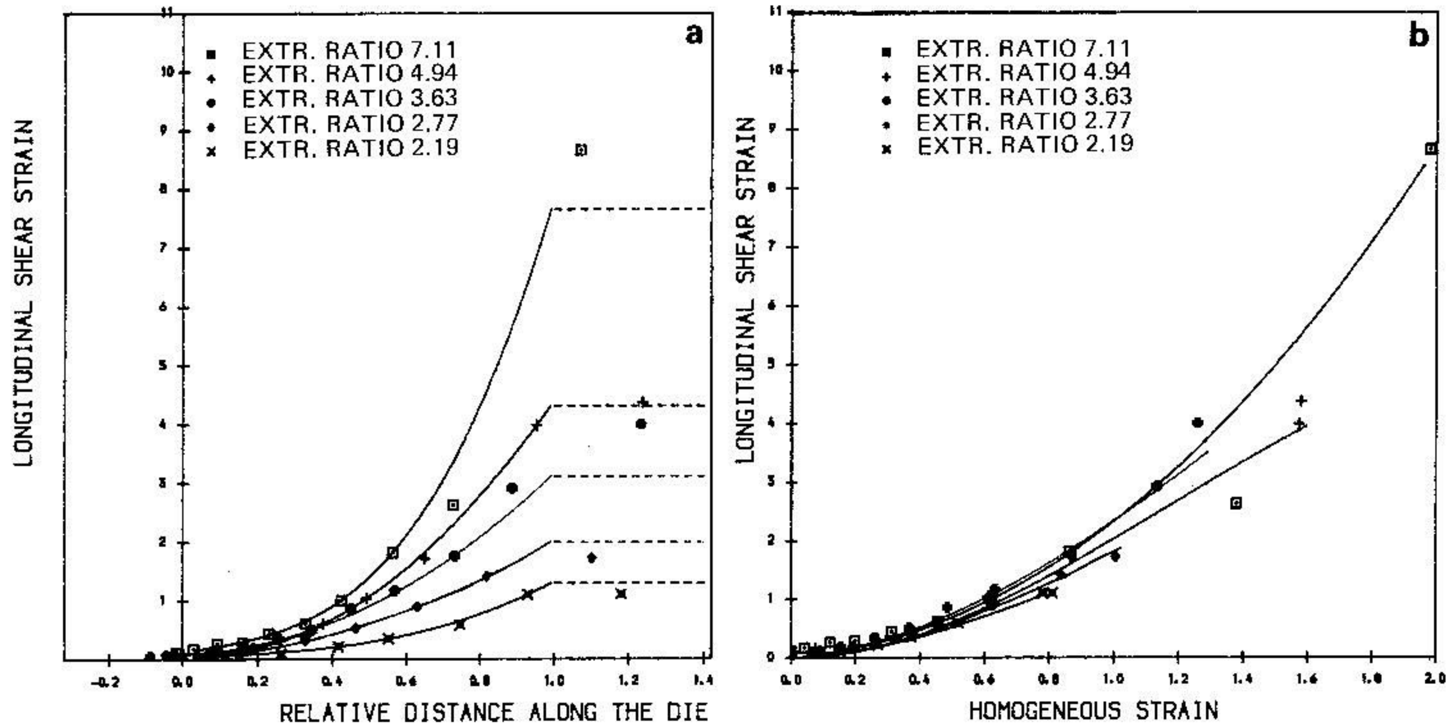

Fig. 7. Conical dies — Set II: Development and variations of the longitudinal redundant strain along the pass and with homogeneous strain.

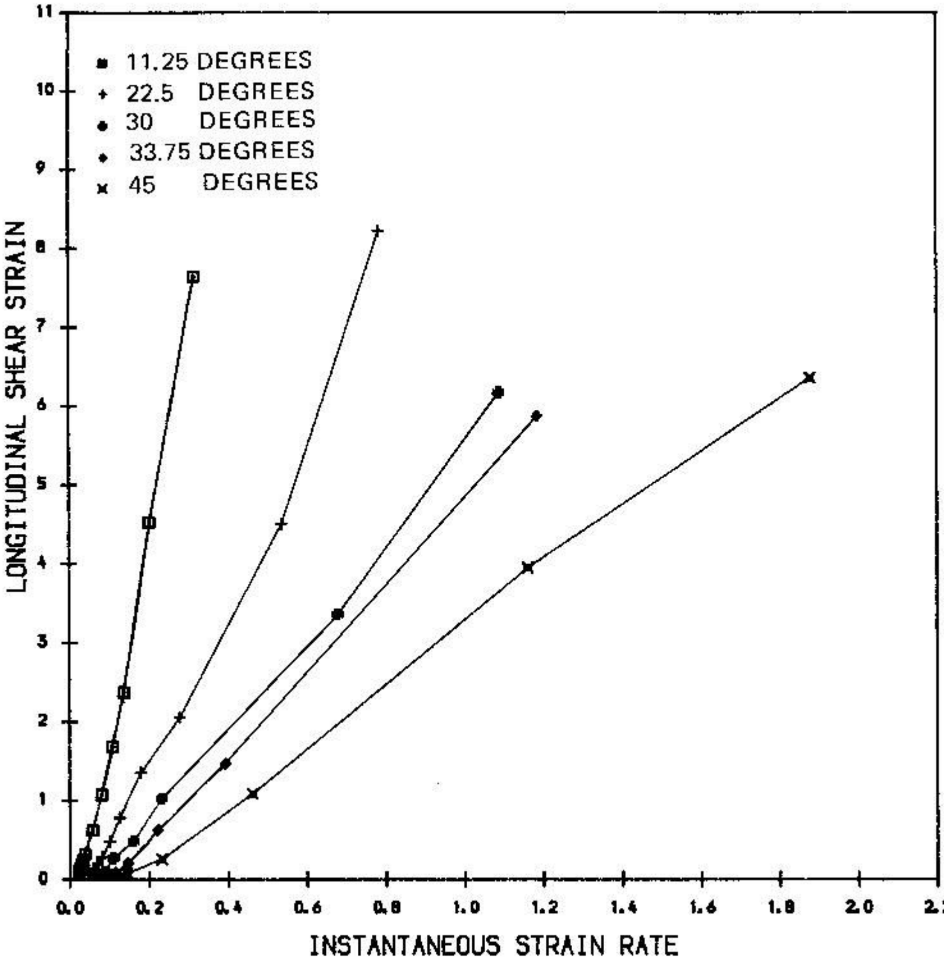

Fig. 8. Conical dies — Set I: Variation of longitudinal shear strain with instantaneous strain rate related to position along the pass.

redundant strain, the working zone of the pass, and the homogeneous strain of deformation imposed on the extrudate.

Die Set I (Fig. 8) produces linear relationships between redundancy and strain rate for given die angles. The redundant shearing strain is clearly proportional to the instantaneous strain rate everywhere along the deformation zone.

The correlation between the patterns of redundant shearing strains and strain rates along the pass in the discussed conical dies, suggests that similar trends should develop in curved dies as well. The CRHS set of tools serves to develop this argument.

From Fig. 1(c), giving the distribution of strain rate along the die, it would

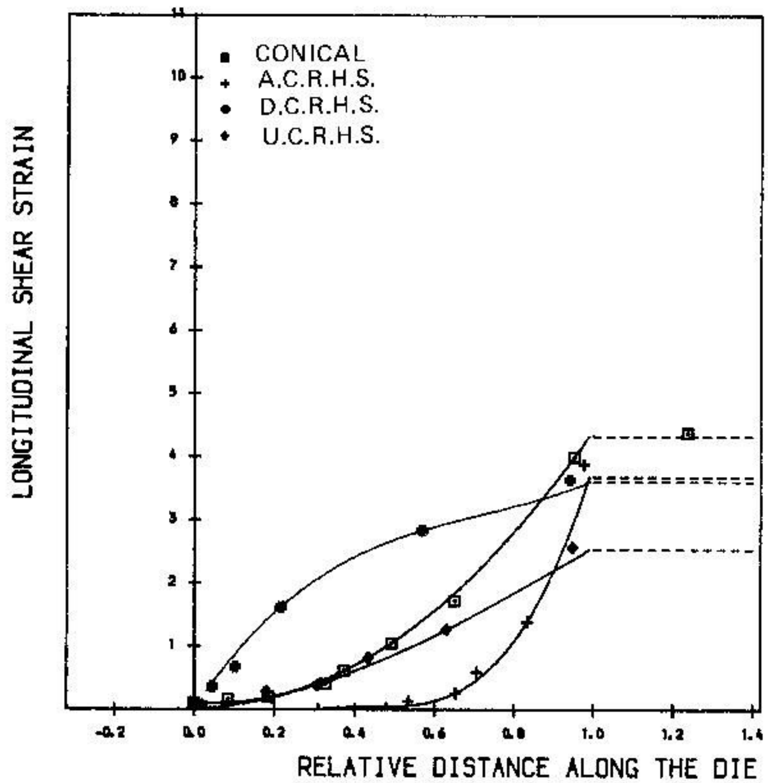

Fig. 9. Variation of longitudinal shear strain along the pass for CRHS dies and a representative conical die.

be expected that, for instance, the shearing strain development in a DCRS tool would show a sharp increase at the beginning and with the decreasing strain rate the curve should tend to level off and attain an almost constant level at the exit from the pass. Similarly at the other extreme of ACRS dies, the curve should increase gradually and, following a sharp increase in the rate, should then display a rapid change in the value of the strain. The experimental results (Fig. 9) support fully this line of reasoning, indicating also an agreement between the rate and strain patterns for conical and URCS dies.

In addition to the variation of the strain rate along the pass, there exists variation across the section related to the radial position in any given transverse plane. A visioplasticity analysis shows that higher values, including the peak of the strain rate, are expected somewhere between the outer surface and the core of the processed specimen. This tendency is confirmed by the experimental results [7] which show that the differentiality in strain rate across the section appears to be the principal reason for the incidence of redundancy. Relative shearing of adjacent layers of material being deformed at different rate will inevitably produce shearing strains on the notional common boundaries. The higher the strain rate the higher will be the degree of non-uniformity of flow.

6. Conclusions

Whereas within certain limits of strain imposed, the validity of the definition of the geometry factor, as given by eqn. (2), is acceptable from a numerical point of view, the effect of strain rate cannot always be neglected. In consequence, a unique — for the material and geometry — relationship between redundancy and pass profile, suggested by eqn. (1), may not be appropriate in certain cases, indicated in the paper, and a correction for the effect of strain rate and non-linearity of strain pattern may be necessary. This can be made by redefining ϕ as for instance, $\phi = C_1 + \Delta C_2 + f(\epsilon^2)$. The exact form of the latter functional form will have to be established at a later date when more numerical data become available.

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