Formulation of a New Generalized Equation for the Axial Force during Cold Extrusion

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Abstract— Slip-line field solutions are utilized throughout the literature upon dealing with prediction of the back pressing force during axi-symmetric plain strain extrusion. Here-after, another solution is offered. An ambitious generalized equation for the computation of the cold extrusion axial force is, systematically, deduced basing upon the slip-line field theory. In order to get a general equation which may be suitable for any friction condition, no dead zone is assumed to exit at the die exit internal inclined surface. Frictional stresses at that surface are assumed to be linearly proportional to the yield strength in shear of the workpiece material. The factor of proportionality ranges between zero for frictionless situations to unity for sticking friction conditions. The proposed equation gives the relationship among the needed pressing force and each of the material yield strength in shear, die inlet radius, radii ratio, die semi-angle of inclination and the friction condition at the workpiece-die exit.

Index Terms— Cold Extrusion, Slip-line theory, Axi-symmetric plain strain extrusion.

NOMENCLATURE

A	The cross sectional area of the die exit inclined surface	(m^2)
Fe	Extrusion pressing force.	(N)
Pe	Extrusion local pressure.	(MPa)
r1	Inlet die radius.	(m)
r2	Outlet die radius.	(m)
R	Radii ratio = r_2 / r_1.	-
θ	Die semi-angle.	(radian)
ϕ	α Slip-line overall starting angle starting from the die internal surface and ending at the die inclined surface.	(radian)
Ψ	Angle between the tangent to the end of a α slip-line at the die inclined surface and that inclined surface.	(radian)
k	A factor related to the friction condition at the die inclined surface which varies between zero for frictionless status and unity for the sticking friction condition.	
τ	The yield strength in shear of the workpiece material (assumed to be constant)	(MPa)

1 Introduction

THE bulk metal forming includes many processes both as classical and modified categories. These classical bulk metal forming processes are still in great demand in many industry sectors. It does not seem that this trend will slow down as new technologies have been developed over recent years. These technologies are continuously modified for new demands [1-2].

Extrusion process has proved its potential in bulk metal forming process since the industrial development due to its high productivity, lower cost and the fact that it increases the physical properties of the materials [3]. The better mechanical property, product quality and the strength of the extruded products are the advantages in extrusion process. The demand raised by society on the extruded product quality has been putting the extrusion industries into pressure for the optimal selection of the process and process variables [4].

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In extrusion, mechanical properties of the extruded material, extrusion ratio, frictional condition between die-workpiece interface, and the die profile are the predominant parameters that directly influence the product quality [5]. Therefore, optimization of metal flow is very important as it directly affects extrusion speed, mechanical properties and surface finish of the extruded products [6]. Metal flow during extrusion can be affected by factors such as material flow properties, die profile, friction conditions, and container work piece heat transfer characteristics [7]. Study of frictional condition and effect of die profile to impart a homogeneous deformation of material flow becomes very complex in analytical way. The axi-symmetric plain strain extrusion had been investigated using the upper-bound, slab, slip-line [8]. The slip-line field theory were used to solve a variety of complex plane plastic flow problems met with during the extrusion of ductile metallic sheets and plates [9]. Reduction of dead metal zone and frictional effect between die- workpiece interfaces ensures the homogeneous metal flow; this has been proved by many researchers by redesigning the die profile. Friction is one of the most significant parameters to be considered in direct extrusion, as the workpiece surface is moving along the container, so the contribution to the required energy can be extremely high [10-11]. Friction reduction in metal forming processes such as extrusion ones contribute to a more efficient per-

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formance of manufacturing processes, as well as to it leads to a decrease in energy consumption during manufacturing [12].

Owing to the rapid development of numerical technology, many researchers have performed some simulation work on extrusion process to provide accurate and theoretical guidance for die design [13]. Various researches in axi-symmetric extrusion field suggested deformation patterns and assessed axial extrusion force. Siebel and Fingmeir [14] tried to forward a rational relationship between the extrusion pressing force and the reduction in the cross sectional area. Such trial was based on the assumption of uniform deformation and allowed for the friction force between the extruded material and the die to be considered. Hill [15] utilized the slip-line field technique to compute the plain strain extrusion pressure, for a non-work-hardening material extruded through square dies in a range of area reduction ranged from 0.12 to 0.88. In this study, dead-metal zones were assumed to spread over the exit surface of the die. Frictionless conditions were assumed to exit during extrusion.

Johnson [16] employed the same technique to arrive at the value of the extrusion pressure for plain strain conditions through square dies for large reductions. Johnson [17] suggested an empirical formula for estimating the axi-symmetric cold plain strain extrusion pressure depending upon a slip-line field solution for moderate reduction lubricated square dies. Wilcox and Whitton [18] and [19] had carried out several measurements of the extrusion pressure during a very wide range of area reductions and die angles. They had also utilized an empirical equation of the same form as proposed in [17]. The influence of die angle, reduction ratio and die land on the extrusion force during the cold extrusion process were investigated by J.S. Ajiboye et al. [20], S.O. Onuh et al. [21] and P. Tiernan et al. [22].

Kudo [23] gave an upper-bound solution for axi-symmetric extrusion. Johnson and Kudo [24] presented a detailed survey of extrusion mechanics. Upper-bound theory has been extensively applied to extrusion of various cases. Such theory is of most use in extrusion for predicting working loads, and, with less accuracy, deformation patterns [25]. Rowe [25] forwarded slip-line field solutions for strip extrusion through tapered dies for different friction conditions. Upper-bound solutions, for plane strain conditions, were also presented. Simple upper-bound field solution for plain strain frictionless extrusion was introduced via the concept of energy dissipation on planes of discrete shear [26- 27].

The present paper present, basing upon slip-line field theory, a generalized equation which predicts the axial back pressing force for axi-symmetric extrusion. The friction condition at die exit surface is taken into consideration in that deduced equation. For the sake of generalization no dead zone is assumed to cover die exit.

2 ANALYSIS

It is known that the general equation of an α-slip line is given by the following relationship [28];

$$P + 2\tau.\phi = consant \qquad (1)$$

(1)

Since at a free surface $P = -\tau$, then the above equation can be re-written in the following form;

$$P = -\tau(1+2\phi) = \left|\tau(1+2\phi)\right| \qquad (2)$$

Figure 1 presents a tentative model for the cold extrusion operation. Workpiece material is assumed to be a non-strain hardened one. The surface finish of the extrusion cylinder, especially at its exit, and to a lesser extent, the extrusion speed may play considerable roles in governing the friction status for the extrusion operation. Nevertheless, such operation has to range between frictionless and complete sticking conditions.

It can be proved, from figure (1), that the relationship between ϕ, θ and Ψ is given by the following equation;

$$\phi = 1.25\pi - \theta - \psi \qquad (3)$$

It follows from Eqs. (2) and (3) that,

$$P_e = \tau.\left|8.854 - 2\psi - 2\theta\right| \qquad (4)$$

From a simple force analysis is; the axial extrusion force (F_e) is given by the relationship;

$$F_e = P_e \times A\sin(\theta) + k.\tau \times A\cos(\theta) \qquad (5)$$

But $A = \pi(r_1^2 - r_2^2)/\sin(\theta)$. If $R = r_2/r_1$ then $A/r_1^2 = \pi(1-R^2)/\sin(\theta)$. Therefore, it can be deduced out of Eqs. (4) and (5) that;

$$F_e / \tau.r_1^2 = \pi(1-R^2)(8.854 - 2\psi - 2\theta + k\cot(\theta)) \qquad (6)$$

It should be noted that the value of the angle (Ψ) is dependent, positively, upon the friction condition at the die inclined exit surface. Hence as (Ψ) increases so do k. If such relationship is assumed to be a linear positive one, then,

$$k = 2\psi / \pi = 0.636\psi \qquad (7)$$

Substituting Eq. (7) in Eq. (6), it follows that,

$$F_e / \tau.r_1^2 = \pi(1-R^2)\left[8.854 - 2\theta - \psi(2 - 0.636.\cot(\theta))\right] \qquad (8)$$

The above equation is claimed to be a generalized equation dealing with the computation of the cold extrusion axial force (F_e) via the ratio ($F_e/\tau.r_1^2$) for given values of τ and r_1 and for any friction condition at workpiece-die inclined exit surface. While the frictionless condition means a value of (ψ) equal to zero; sticking friction condition gives the angle (ψ) a value of $\pi/2$.

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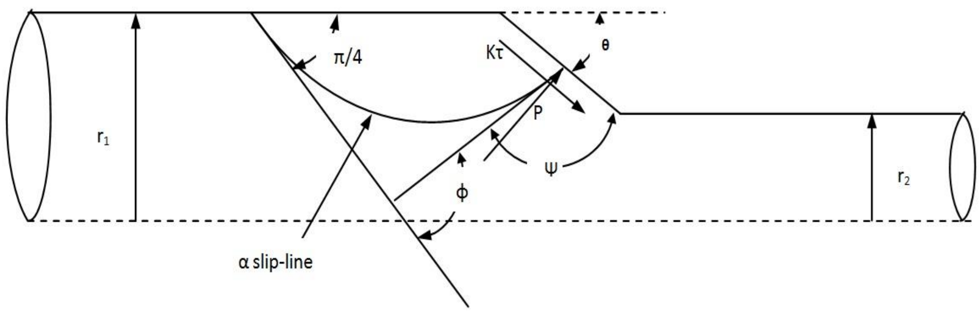

Fig. 1. An outline of the extrusion operation together with the particularities of the proposed model.

3 RESULTS AND DISCUSSION

Figures from 2 to 8 give graphical representations for the proposed generalized viz. Eq. (8). Such graphs were obtained, upon computing the values of normalized forces ($Fe/\tau.r_1^2$), as functions of the angle (θ) for different values of (R) and (Ψ). Owing to the nature of equation (8), a perfect straight line could be resulted from positive correlations exit among (Fe) and both of τ and r_1^2. The normalized force ($Fe/\tau.r_1^2$) is found to decrease for higher die semi-angle (θ), greater radii ratio (R) and lighter friction condition which is manifested by smaller angle (Ψ) (as shown in Figs. 2 to 8).

Straight line relationships tend to exit, in general, between the normalized force ($Fe/\tau.\ r_1^2$) and the die semi-angle (θ) when its value become higher. The differences in these forces for different values of radii ratios (R) become lesser for severer workpiece-die exit friction conditions (higher values of the angle (Ψ)). Dramatic changes in the values of the normalized force ($Fe/\tau.\ r_1^2$) are very noticeable, in general for die semi-angles (θ) within the range 0°- 10°.

An increase in (R) by 0.25 is found to cause unequal drop in the normalized force value starting from a given value of (R). For instance, an increase in (R) from 0.25 to 0.50 is found to cause a smaller drop in the values of normalized forces than that corresponding to increase in (R) from 0.50 to 0.75 (see Figs. 2 to 8). The normalized forces are found, for all cases of friction conditions, to drop to 80% of their former value when (R) increase from 0.25 to 0.50. On the other hand, such forces drop and become, only, 58% of their former values if (R) increase from 0.50 to 0.75.

That is understandable since the normalized force ($Fe/\tau.\ r_1^2$), according to Eq. (8), is proportional to ($1-R^2$). The values of the normalized force for different values of (R) become closer to each other as the die-semi angle (θ) become bigger. The relationships ($Fe/\tau.\ r_1^2$) versus (θ), for all values of (R), seem to emerge from a common origin at very high values of (θ) for the same friction condition (same (Ψ)).

Figure (2) merit special attention. It represents the workpiece-die frictionless condition (the angle (Ψ) is equal to zero). In such a case, Eq. (8) yield negative straight line for the relationships between ($F_e/\tau.r_1^2$) and (θ) all over the entire range of die-exit-semi angles for any given value of (R). Huge increases are noted in the values of axial force (F_e) for the sticking friction condition (figure (8)) as compared with the frictionless condition (figure (2)). As the friction condition get severer (higher values of (Ψ)) so do the value of the cold extrusion axial force.

4 CONCLUSION

A new generalized equation for the axial force during cold extrusion had been formulated based on slip-line field theory. The friction condition at die exit surface is taken into consideration in that deduced equation. For the sake of generalization no dead zone is assumed to cover die exit. The following conclusions can be drawn:

1. The normalized force is found to decrease for higher die semi-angle (θ), greater radii ratio (R) and lighter friction condition which is manifested by smaller angle (Ψ).
2. At higher workpiece-die exit friction conditions, the radii ratios had insignificant influence on the extrusion axial force for different values of radii ratios.
3. At higher die semi-angle, straight line relationships tend to be yielded between the normalized force and the die semi-angle.
4. Dramatic changes in the values of the normalized force can be highly noticeable for die semi-angles (θ) within the range 0°- 10°.

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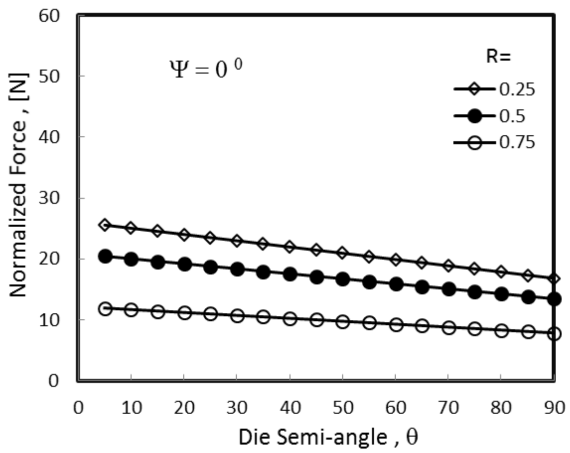

Fig. 2 Normalized force versus die semi-angle for the friction-less condition (Ψ=0º).

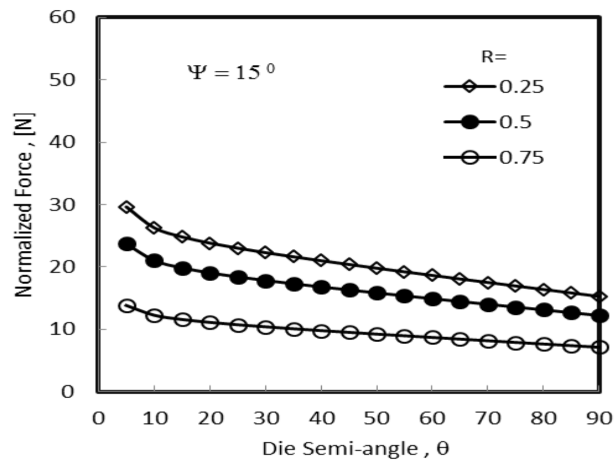

Fig. 3 Normalized force versus die semi-angle for the friction-less condition (Ψ=15º).

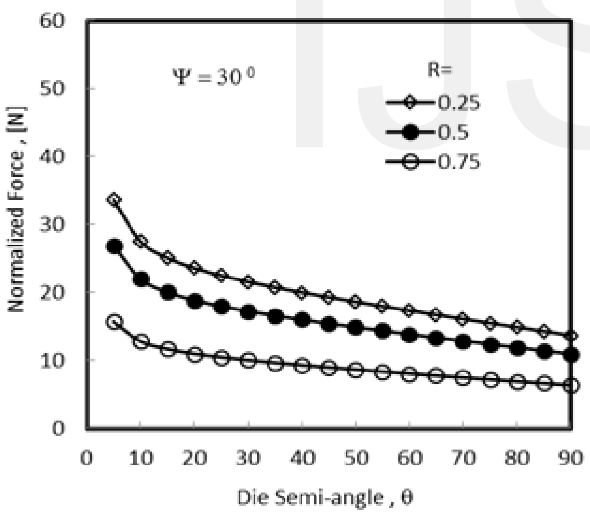

Fig. 4 Normalized force versus die semi-angle for the friction-less condition (Ψ=30º).

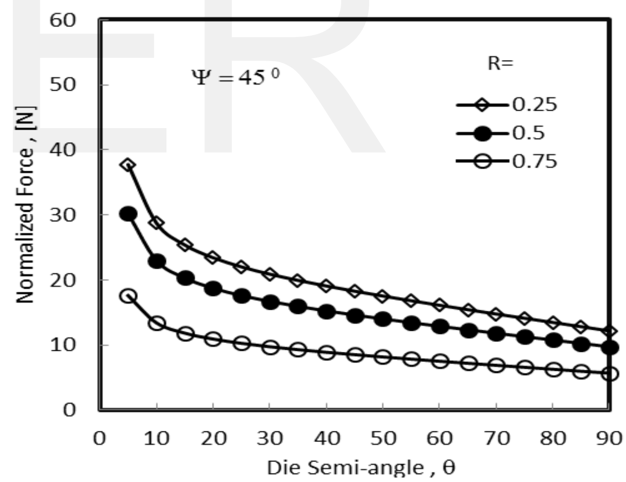

Fig. 5 Normalized force versus die semi-angle for the friction-less condition (Ψ=45º).

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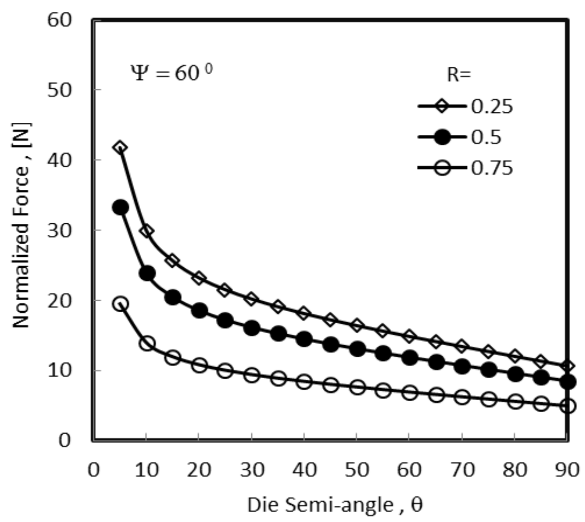

Fig. 6 Normalized force versus die semi-angle for the frictionless condition (Ψ=60º).

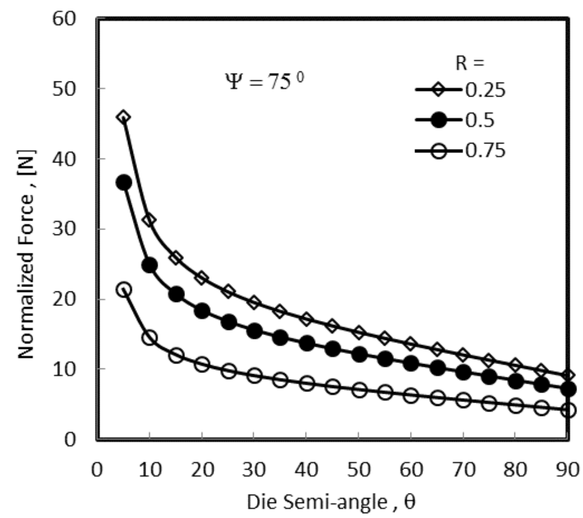

Fig. 7 Normalized force versus die semi-angle for the frictionless condition (Ψ=75º).

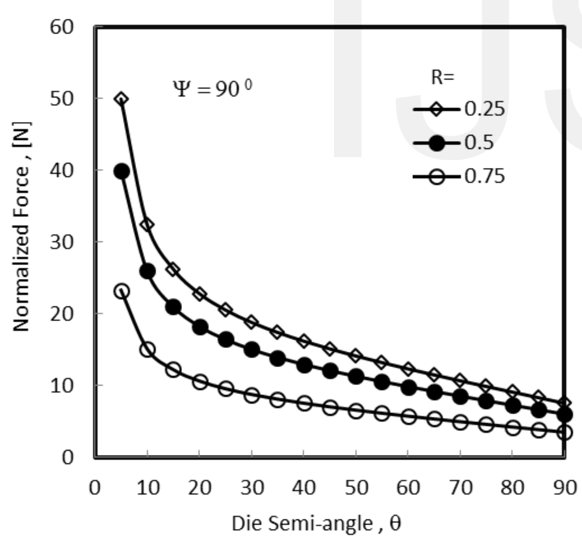

Fig. 8 Normalized force versus die semi-angle for the frictionless condition (Ψ=90º).

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