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Technical Paper

Analytical modeling of hydrodynamic lubrication in a multiple-reduction drawing die

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ABSTRACT

The hydrodynamic lubrication regime is reported to exist in numerous metal forming applications, such as wire drawing and hydrostatic extrusion, but it is difficult to achieve in the drawing of large diameter rods due to the relatively low drawing speeds common for larger parts. By creating a stable fluid film between the workpiece and the die during the drawing process friction and die wear could be significantly reduced, leading to energy savings, increased achievable reductions, and increased die life. An analytical model of the hydrodynamic drawing process is proposed which considers the geometry of the workpiece and die, as well as, the material properties (including work hardening effects), and (temperature dependent) fluid properties to determine the fluid film thickness over the reduction die. This model is then used to analyze several case studies, including a multiple reduction die with high pressure lubricant supplied to the space between the dies. It is shown that a stable fluid film can be established for low drawing speeds through the combination of a multiple reduction die and a supply of lubricant at high pressures to the inlet of the dies.

1. Introduction and motivation

Lubrication is a critical part of the metal forming process, as it can have effects on frictional forces, tool wear, material flow, and achievable reductions. Therefore, a great deal of effort has been put into characterizing and predicting lubrication properties for nearly every metal forming process. Lubrication in the metal forming process can be categorized into three regimes, i) boundary lubrication, ii) mixed lubrication, and iii) hydrodynamic lubrication, which are differentiated by the amount of lubricating fluid in between the die and workpiece during the deformation process as shown in Fig. 1. Boundary lubrication takes place with little to no liquid lubricant between the two surfaces and, thus, the majority of the deformation load is carried by the surface asperities of the parts. Hydrodynamic lubrication occurs when an uninterrupted liquid lubricant film is established between the tools and workpiece, which results in the entire deformation load being carried by the lubricant. Mixed lubrication occurs when the thickness of the fluid film is not great enough to completely separate the two surfaces, resulting in some of the deformation load being carried by the surface asperities of the workpiece and some of the load being carried by the lubricant. The frictional stresses in the system will generally be reduced as the share of the load carried by the liquid lubricant increases. This is because of the low amount of shear stress which is required to cause a fluid to flow, meaning that not much shear stress is created as a result of the difference in speeds between the workpiece and die. Thus the hydrodynamic lubrication regime is attractive to metal forming processes designers hoping to reduce friction, increase tool life, and improve material flow [1].

The occurrence of the hydrodynamic lubrication regime in the near net shape forming of metal parts is well known and has been widely studied. In the 1950's and 60's it was discovered that hydrodynamic lubrication regime was present, or could be achieved in numerous metal forming processes. For example, Christopherson and Naylor discovered how to encourage the formation of a hydrodynamic film in the wire drawing process by pressurizing the lubricant at the die inlet to near the yield point of the wire and derived relationships between the various parameters in the fluid film [3]. Once it was established that hydrodynamic lubrication was achievable in the drawing process, other researchers attempted to improve the equations describing the hydrodynamic film by re-deriving them using varying assumptions and solution strategies [4–6]. Other continuous processes, such as extrusion [7–9], strip rolling [10–12], and even strip drawing [13], were also examined under hydrodynamic lubrication conditions. In general, the film thickness is affected by the surface speeds of the tools and workpiece, the viscosity of the lubricant, and the geometry of the interface. In general, increase in the lubricant viscosity and decrease

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Nomenclature

$\mathbf{A}_3$	Area of 3rd control surface
$\mathbf{A}_{C.V.}$	Area of control volume projected onto x-y plane
B	Update constant
$\mathbf{D}, \mathbf{D}_o, \mathbf{D}_f$	Instantaneous workpiece diameter, original workpiece diameter, final workpice diameter
$\mathbf{c}_{pw}$	Specific heat of the workpiece
$\dot{\mathbf{E}}_p, \dot{\mathbf{E}}_k, \dot{\mathbf{E}}_w, \dot{\mathbf{E}}_{tot}$	Rate of energy brought into/out of control volume by pressure, kinetic energy of fluid, work on the control surfaces, net rate of mechanical energy entering/ leaving C.V.
$\mathbf{h}, \mathbf{h}_i, \mathbf{h}_1, \mathbf{h}_2$	Instantaneous fluid film thickness, fluid film thickness at the inlet to the reduction zone, thickness at control surface 1, at C.S. 2
K	Material strength coefficient
k	Conductivity of lubricant
m	Shear friction factor
$\vec{N}$	Unit normal to the control surface
n	Strain hardening exponent
$\mathbf{P}, \mathbf{P}_o$	Instantaneous fluid pressure, static fluid pressure at the inlet of the draw
Q	Volumetric flow rate of the fluid
q	Dummy variable for inlet zone analysis
$\mathbf{q}_{gen}$	Heat generated in control volume per unit volume
$\mathbf{q}_{die}, \mathbf{q}_{workpiece}$	Heat flux per unit area to the die, to the workpiece
r	Radial direction
$\mathbf{r}_1, \mathbf{r}_c$	(in thermal analysis) Radius of the die at the start of the solution step, radius to the centroid of the control volume
S	Step size (x-direction)
SA/Vol	Instantaneous surface area to volume ratio
$\mathbf{T}, \mathbf{T}_w, \mathbf{T}_d, \mathbf{T}_{old}, \mathbf{T}_{new}, \mathbf{T}_{FD}$	Temperature, temperature of workpiece surface, die surface, workpiece temp. at beginning of solution step, end of step, die surface temp. predicted by finite difference analysis
t	Time required for a portion of the workpiece to move from one step in the solution to the next
U	Instantaneous velocity of the metal
$\mathbf{u}, \mathbf{u}_1, \mathbf{u}_2$	Velocity of the fluid, velocity of fluid at control surface 1, at C.S. 2
V	Velocity of the product
$\mathbf{Vol}_{C.V.}$	Volume inside control volume
v	Velocity of undeformed billet
$\mathbf{v}_s$	(in thermal analysis) Velocity of workpiece surface
$\mathbf{W}_P$	Heat released by plastic work
$\mathbf{x}, \mathbf{x}_o, \mathbf{x}_f$	Distance along the die wall, distance to start of reduction zone, distance to end of reduction zone
$\mathbf{x}_c$	(in thermal analysis) Horizontal distance to centroid
Y	Initial yield stress of workpiece
y	Distance perpendicular to the die wall
$\mathbf{y}_c$	(in thermal analysis) Vertical distance to centroid
$\mathbf{Z}_i$	Distance from the intersection of the die and workpiece to the start of the conical die section
z	Distance measured along the drawing axis
$\boldsymbol{\alpha}$	Half angle of the die
$\boldsymbol{\beta}$	Pressure viscosity exponent
$\boldsymbol{\delta}$	Temperature viscosity exponent
$\boldsymbol{\varepsilon}$	Effective strain in the workpiece
$\boldsymbol{\theta}$	Circumferential direction
$\boldsymbol{\eta}, \boldsymbol{\eta}_i$	Fluid viscosity, fluid viscosity under no pressure and ambient temperature condition
$\boldsymbol{\rho}_w, \boldsymbol{\rho}_f$	Density of the workpiece, density of the lubricant
$\boldsymbol{\sigma}_y, \boldsymbol{\sigma}_z$	Flow stress of workpiece, axial stress in workpiece
$\boldsymbol{\tau}, \boldsymbol{\tau}_w, \boldsymbol{\tau}_s$	Shear stress in the fluid film, shear stress on workpiece surface, shear stress on control surface

in the contact angle result in a thicker lubricant film and the speed of the draw must be kept in an optimum range to pull the lubricant into the reduction area without causing overheating of the lubricant.

Due to the low drawing speeds which are used to mitigate the power required to draw large diameter parts, it is not currently possible to achieve the hydrodynamic lubrication regime in the drawing of large diameter parts using conventional drawing processes. However, there is some evidence to support the idea that hydrodynamic film could be created in large diameter (low speed) drawing processes. Several die configurations designed to assist in the formation of hydrodynamic lubrication films when the conditions would otherwise not support the formation of a thick lubricant film are proposed in Schey's book *Tribology in Metal Working: Friction, Lubrication, and Wear* [14]. In particular, the concept of a hydrostatic die that uses the plastic deformation of the workpiece to create a sealed chamber where pressurized lubricant could be supplied to augment the thickness of the lubricant film is very promising. Experiments done by Pender and Ngaile also concluded that this type of die could be used to establish hydrodynamic films in slow moving drawing operations [15]. If the conditions to create a stable hydrodynamic fluid film could be created even at the relatively low drawing speeds commonly used to draw large parts, there could be significant savings in energy, a reduction in the need to use harsh lubricants and conversion coatings, and a reduction in the die wear rate. These benefits can significantly reduce the costs associated with the drawing of large diameter parts. Therefore, the objectives of this study are to i) derive the equations which govern the thickness of a hydrodynamic fluid film in a multiple reduction drawing process with augmented inlet pressure from first principles, and ii) determine the conditions required to form a hydrodynamic lubrication film at low drawing speeds.

As one would expect the complexity of the differential equations which describe the hydrodynamic film in a drawing process increases immensely when the parameters that describe the workpiece, fluid, and die are allowed to change as a function of the process variables. Frequently, this results in the modeler ignoring relationships which are 'insignificant' to simplify the problems to the point where they can be solved. In the case of hydrodynamic lubrication, the relationships which are most frequently ignored are i) the elastic deformation of the structures over which the fluid flows, ii) out of plane fluid flow (side leakage), and iii) the effects of temperature on fluid properties. However, in some cases these assumptions can lead to errors in the analysis that reduce the applicability of the derived model.

In the case of hydrodynamic lubrication in the drawing process the changes to the flow stress of the workpiece due to the plastic deformation of the workpiece are frequently ignored by modelers. One of the simplifications is to assume that material exhibits perfectly plastic stress-strain behavior. This assumption may not be appropriate for materials that have a large amount of strain hardening like stainless steel and copper. A hydrodynamic model that accounts for strain hardening of the workpiece is preferable because it can be applied to more materials. Elastic deformations in the workpiece and dies are also ignored in most analysis because the dies are very rigid compared to the workpiece and it has been shown that elastic deflections on the workpiece play little effect on