Die Design, Die Pressure & Die Wear

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The improved properties of a novel family of new die materials enable new technical approaches and thoughts regarding classical die design.

As product demand and cost-cutting strive for higher productivity, the limitations of conventional die materials have become more apparent and other alternatives must be explored. Tungsten-carbide-based wire drawing dies have been an industry standard for the past 75 years and are still widely used today. Many companies have traditional, established wire drawing lines using these materials, but as trends are increasingly moving toward higher drawing speeds, the lifetimes of these materials are insufficient.

In particular, Tough Coated Hard Powders (TCHPs) are establishing themselves in the market to fill the gap between tungsten-carbide and diamond materials, and in some cases replacing diamond dies due to diamond's chemical reactivity with steel wire. TCHP wire drawing dies are similar to tungsten carbide in operation and wire surface finish, but offer a service life several times that of their carbide-based counterparts. Die pressure analyses presented in this article illustrate means for maximizing this new service life potential.

A recent paper addressed the drawing of steel with long-life TCHP dies, considering a number of relationships of die pressure to die performance, all derivable from a general **Archard**-type wear equation:

$$\frac{V}{L} = \frac{KF}{H} \qquad (1)$$

where V is the volume of material worn away, L is the sliding distance, F is the force between the two sliding media, H is the hardness of the material being worn and K is a proportionality constant.[1] With respect to the specific application of wire die wear, the quantity L is simply the length of wire drawn. The quantity V is simply the area, A, of the cylinder of contact between the wire and the die, multiplied by the average depth of the die surface that has been worn away. This depth is $\delta/2$, with δ simply being the average die diameter increase due to wear. Finally, it is useful to replace the contact force with the product of the average die pressure, P, times the contact area, A. With these substitutions, equation (1) can be restated in the following useful forms.

The increase in diameter of wire exiting the die due to wear may be expressed as:

$$\delta = P\frac{2LK}{H} \qquad (2)$$

The length of wire that may be drawn for a given average die diameter increase is:

$$L = \frac{H\delta}{2KP} \qquad (3)$$

The die life in time, t, is simply L / S, where S is the drawing speed, and hence:

$$t = \frac{H\delta}{2SKP} \qquad (4)$$

Finally, the mass, m, represented by length, L, is simply:

$$m = \frac{\pi}{4}L\rho d^2 \qquad (5)$$

where ρ is the wire density and d is the as-drawn wire diameter.

Drawing die wear phenomenology is seen in **Figure 1** (note difference in vertical and horizontal scales).[2] While a relatively consistent degree of wear develops in the drawing channel, a concentration of wear typically occurs at the locus of initial wire-die contact. This concentration of wear is referred to as the "wear ring" and is generally the first stage of wear visible upon casual inspection of the die.

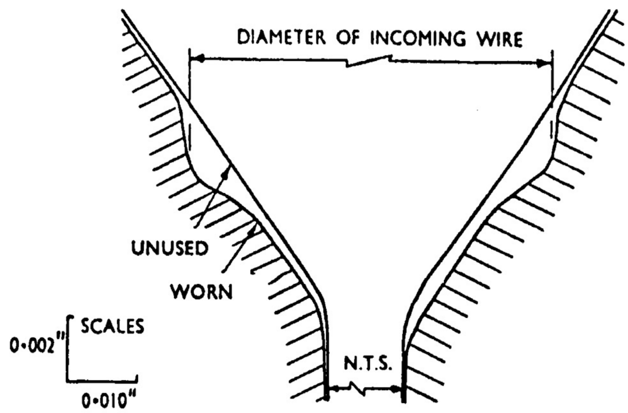

Fig. 1 — Drawing die wear phenomenology, displaying a "wear ring" at the locus of initial wire-die contact. Note difference in horizontal and vertical scales.[2]

The expressions of wear in equations (2) through (5) are all directly related to the die pressure, and the average die pressure can be estimated from the classical relationship:

$$\frac{P}{\sigma_a} = 0.25\Delta + 0.6 \qquad (6)$$

where σ_a is the average flow stress (or strength) of the wire during drawing, and where

$$\Delta \approx (\alpha / r)\,[1 + (1\text{-}r)^{1/2}]^2 \qquad (7)$$

where α is the "half-angle" or "semi-angle" in radians (with the "included angle" of the die being 2α), and r is the decimal drawing reduction (an r of 0.1 is the same as a 10% reduction, etc.).[3,4]

It has been known for some time that the die pressure is not constant throughout the drawing channel, but rather is higher at the entrance and exit of the drawing channel. Thus, the average die pressure projections of classical analysis are rather incomplete. In this context, this article presents a more detailed look at the die pressure distribution in wire drawing, through the medium of finite element modeling (FEM). These analyses provide a more sophisticated understanding of the roles of drawing parameters in affecting or controlling die wear. Such understanding is especially useful in assessing the advantages and performances of long-life TCHP dies.

Finite Element Modeling of Die Pressure

The basic procedure of finite element analysis begins with a geometric scenario, in this case a wire and die, which is discretized in order to perform classical mechanical calculations on the discrete points. Information is added by the user with regard to material characteristics, structural movements and interactions. For a dynamic analysis such as for wire drawing, there is an iterative process wherein a stress state at a given time is determined, and this solution is then used as the initial condition in the following "time-step". The simulation data provided in this article represent one of these discrete time-steps under steady-state drawing conditions.

The finite element simulations in this article were performed using an *ANSYS (v.11)* software package. For simplification, a 2-D axisymmetric model was chosen, with the material deformation of the wire material being dictated by a yield criterion equal to the material flow stress. Upon completion of the core model, several parameters can be easily augmented such as geometries (die/wire), physical interactions (friction), material properties (yielding/hardening) and process variables (drawing speed, reductions, etc.). In examining the matrix of conditions set forth in **Table 1**, a constant value of flow stress was assumed—namely 1700 MPa, and an exit wire diameter of 0.463 mm was used. The resulting FEM calculations are presented in **Figure 2** and **Figure 3**, and on the next page in **Figure 4** and **Figure 5**.

For the 15% and 20% reductions, the die pressure is seen to increase to a maximum near the die entry, followed first by a decline and an increase near the die exit. The pressure distribution is similar for the 10% reductions, but with little manifestation of a pressure maximum near die entry. It should be noted, however, that the die contact length (horizontal axis) is nondimensional. That is, the nondimensional value represents the actual distance downstream from the initial pressure development, divided by the total length of the region bearing pressure. Therefore, the downstream shift in pressure peak with nondimensional contact length to be noted for lesser reductions is exaggerated.

Nonetheless, in **Figure 2**, for example, the pressure peaks are about 0.035, 0.040 and 0.05 mm downstream from the locus of initial pressurization for the respective reductions of 20%, 15% and 10%. **Table 1** summarizes the values of average pressure, maximum entry pressure and exit pressure for the matrix of conditions subjected to FEM modeling.

Table 1. Die Pressures for a Matrix of Drawing Passes, Based on Figures, 2, 3, 4 and 5.

Drawing Reduction	Included Die Angle	Friction Coefficient	Delta	Average Pressure	Maximum Entry Pressure	Exit Pressure
10%	8°	0.03	2.66	1760 MPa	1950 MPa	1990 MPa
10%	8°	0.10	2.66	1710	1920	1930
10%	12°	0.03	3.99	2270	2530	2540
10%	12°	0.10	3.99	2220	2470	2620
15%	8°	0.03	1.72	1630	1970	1880
15%	8°	0.10	1.72	1520	1940	1670
15%	12°	0.03	2.59	1810	2210	1790
15%	12°	0.10	2.59	1740	2110	1710
20%	8°	0.03	1.26	1500	2050	1640
20%	8°	0.10	1.26	1280	1960	1350
20%	12°	0.03	1.88	1530	2040	1680
20%	12°	0.10	1.88	1440	2020	1550

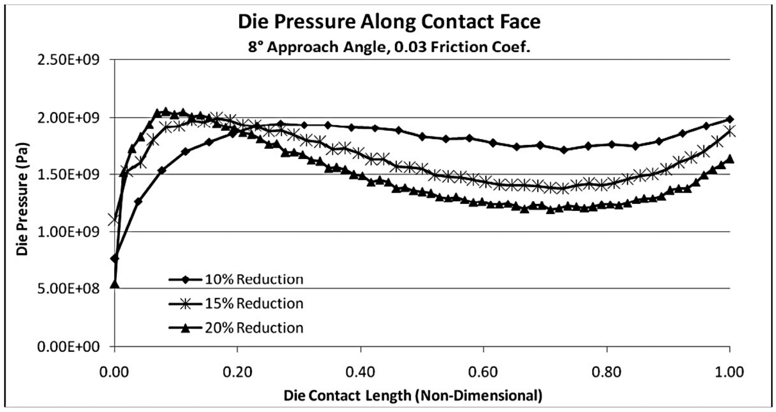

Fig. 2 — Die pressure along wire-die contact length for an 8° included angle, a coefficient of friction of 0.03 and for three reductions.

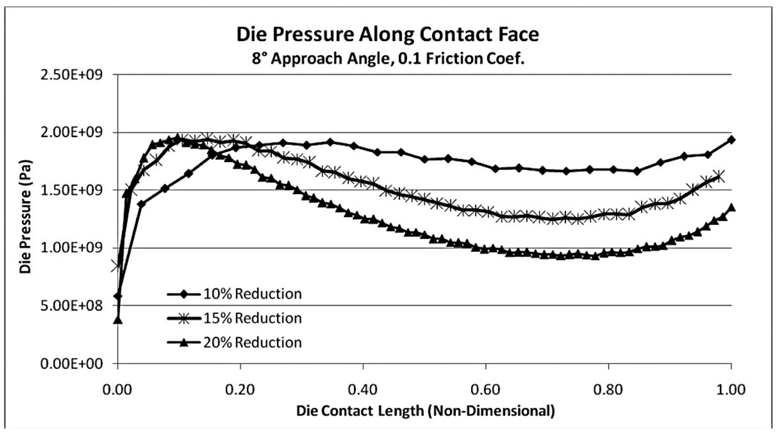

Fig. 3 — Die pressure along wire-die contact length for an 8° included angle, a coefficient of friction of 0.10 and for three reductions.

It should be appreciated that the die pressure increase at die entry is not instantaneous, but rather suggests an elastic bulging effect (plastic bulging will occur at high Δ values). On the other hand, the die pressure decrease at the drawing zone exit is rather abrupt, consistent with the "sucking down" of the wire (again, an effect that can be substantial at high Δ values). **Continued...**

Relationships to Delta

As set forth in equations (6) and (7), the deformation zone shape parameter, Δ, has been useful in projecting approximate values of die pressure. Thus, it is not surprising that the FEM data shown in this article can be correlated with Δ, as per the following linear regressions:

$$(P_{a,\,0.03}) / \sigma_a = (0.17)\Delta + 0.63 \quad (8)$$

$$(P_{max,\,0.03}) / \sigma_a = (0.11)\Delta + 1.00 \quad (9)$$

$$(P_{ex,\,0.03}) / \sigma_a = (0.18)\Delta + 0.70 \quad (10)$$

$$(P_{a,\,0.10}) / \sigma_a = (0.20)\Delta + 0.51 \quad (11)$$

$$(P_{max,\,0.10}) / \sigma_a = (0.11)\Delta + 0.97 \quad (12)$$

$$(P_{ex,\,0.10}) / \sigma_a = (0.26)\Delta + 0.45 \quad (13)$$

where the pressure subscript 0.03 or 0.10 designates the coefficient of friction, and where P_a, P_{max} and P_{ex} denote the average pressure, maximum entry pressure and exit pressure, respectively, for the FEM projections.

Discussion

Equation (8) is based on conditions roughly comparable to the studies of **Wistreich** that are the basis of classical projections such as equation (6).[5] While there is similarity, at a Δ value of 2, for example, the classical formula predicts an average P/σ_a value of 1.1, whereas equation (8) predicts a value of 1.0.

In general, the average pressure values of this FEM analysis are somewhat below the values that are implied by the classic split-die measurements of Wistreich. However, in this study, the general correlations with respect to Δ are clear and consistent with classical analysis.

The dependence of maximum entry pressure on Δ is less than that of the average pressure, with coefficients in equations (9) and (12) only about 60% of the coefficients of equations (8) and (11). On the other hand, the exit pressure dependence is somewhat greater than that of the average pressure, with coefficients in equations (10) and (13) larger than the coefficients of equations (8) and (11).

It is clear that the increase in coefficient of friction from 0.03 to 0.10 involves a 3% to 10% decrease in die pressure, although the higher friction is associated with a greater sensitivity to Δ insofar as the coefficients of equations (11), (12) and (13) are larger, on average, than those of equations (8), (9) and (10).

The maximum entry pressure may be associated with the concentration of wear at the wear ring, although it must be appreciated that fatigue from fluctuations in wire diameter and vibrations (etc.) also affect wear ring locations.

The exit pressure surely affects wear of the blend region, between the drawing channel and the bearing length.

While, in general, it remains that overall die pressure increases with Δ, the FEM analysis presented in this article provides a detailed description of the longitudinal pressure gradient, discriminating among regions of wear ring development, general drawing channel wear and wear at the blend. All three regions have practical impact on die life, contributing to the wear rates set forth in the Archard equation.

However, the implications of each are somewhat unique. The wear ring is often the first observed manifestation of wear and may impede lubricant entry and promote bulging. Wear in the blend area has the effect of decreasing the average die angle (perhaps fortuitously) and shortening the bearing. Wear in the drawing channel may best relate to the basis for overall die lifetime.

In any case, a sophisticated appreciation of die pressure and die wear relationships is fundamental to good die design and to obtaining the maximum life from high performance TCHP dies.

Summary

This article has presented a detailed look at the die pressure distribution in wire drawing, through the medium of finite element modeling (FEM). These analyses provide a more sophisticated understanding of the roles of drawing parameters in affecting or controlling die wear.

A general correlation of die pressure with Δ is evident, consistent with classical analysis. However, the FEM analysis provides a detailed description of the longitudinal pressure

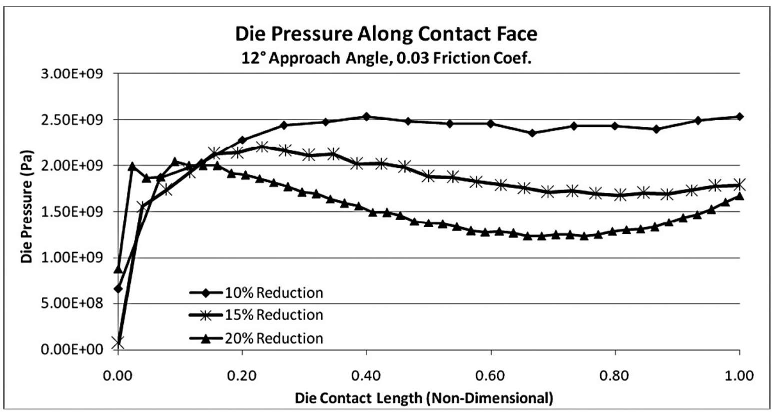

Fig. 4 — Die pressure along wire-die contact length for a 12° included angle, a coefficient of friction of 0.03 and for three reductions.

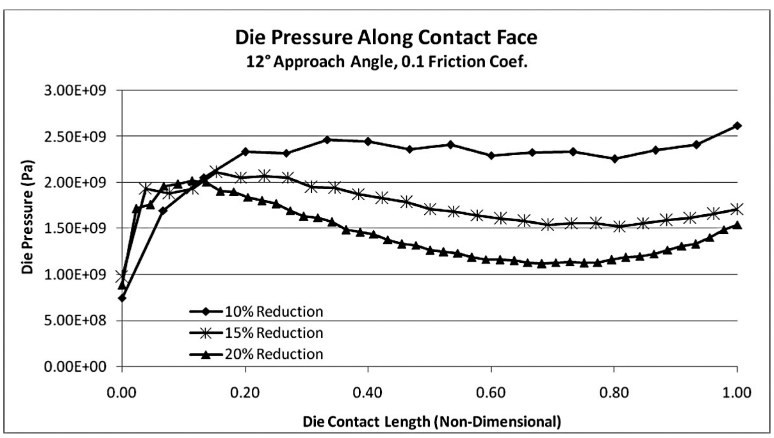

Fig. 5 — Die pressure along wire-die contact length for a 12° included angle, a coefficient of friction of 0.10 and for three reductions.

gradient, discriminating among regions of wear ring development, general drawing channel wear and wear at the blend. The dependence of maximum die entry pressure on Δ is less than the dependence of the average pressure on Δ. An increase in coefficient of friction involves a decrease in die pressure, although higher friction is associated with a greater sensitivity of die pressure to increases in Δ. Understanding these phenomena allow end users to optimize their drawing lines not only for increases in final wire quality, but for extended die life via improved die design. The implementation of these technologies is currently being used for TCHP dies in order to further extend their service lifetime over conventional materials.

To obtain additional information on TCHP wire drawing dies, contact the authors or visit the website listed below.

www.allomet.net **WCTI**

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[4] *R. N. Wright, Wire Technology - Process Engineering and Metallurgy, Butterworth-Heinemann, Oxford, UK, 2011, p. 35.*

[5] *J. G. Wistreich, Proceedings of the Institution of Mechanical Engineers, 1955, Vol. 169, p. 654.*

Company Profile...

Allomet Corporation *produces and markets a family of sintered composite pseudoalloys that can be engineered to combine hardness approaching that of diamond with fracture toughness greater than tungsten carbide and weight approximately that of titanium. This new class of designed-microstructure particulate materials is called Tough-Coated Hard Powders (TCHP or EternAloy®).*

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Rensselaer Polytechnic Institute (RPI) *is the oldest technological university in the USA. RPI offers degrees from five different schools. These include Engineering; Science; Architecture; Humanities, Arts and Social Sciences; and the* ***Lally School of Management & Technology****; as well as an interdisciplinary degree in Information Technology.*

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