

---

# THEORY OF WIREDRAWING

## *Introduction*

Prior to the adoption of continuous drawing practices, little attention was given to understanding wiredrawing theory. This can be largely attributed to the fact that, until the introduction of steam power, the single, largest problem facing wiredrawers was obtaining the necessary motive force required for the drawing process. As developments and improvements in mechanization developed during the Industrial Revolution, little emphasis was placed on understanding the physical process, as satisfactory results were generally obtainable with the moderate drawing speeds and drafting that were used. In any event, wire could be processed only in low volume as short die life limited any further increases in productivity and quality. However, commercial introduction of cemented carbide dies in Germany during the 1920s resulted in an increase in drawing speeds and sophistication in wire mills to handle the larger volumes that could be drawn. Therefore, it was soon apparent that a more detailed understanding of the wiredrawing process was needed.

While an impressive body of knowledge has accumulated that affords a comprehensive picture of single-hole wiredrawing, additional detail is needed, particularly for multi-hole processes. Modern wiredrawing is a highly competitive global business where product requirements are continuously changing and the traditional evolutionary or “Edisonian” techniques, which characterized technology development in the past, are no longer viable. Furthermore, given the limited resources that are available in the industry as well as the rapidly changing technical requirements, it is clear that personnel at all levels need an in-depth understanding of wiredrawing theory. It is

also clear that such an understanding is a prerequisite for controlling and optimizing existing processes and the sustainable development of new technology.

### ***Mechanics of Wiredrawing***

Deformation in wiredrawing is influenced by a number of factors; wire chemistry, approach angle, lubrication, drawing speed, and reduction are the most significant. The primary emphasis in wire-drawing mechanics is on understanding and defining the relationships that exist between these process conditions and the resulting thermo-mechanical response of the wire. Many of the technological developments that have taken place in wiredrawing over the past 20 years have been the result of an increased understanding of these relationships.

### ***Constancy of Volume***

Although the fact that volume is not lost during deformation may seem obvious, it is, in fact, a highly useful concept that forms the basis for analyzing a number of wiredrawing problems. One of the most common applications involves the determination of wire speed at different stands and the necessary capstan speeds that should be used. Simply stated, constancy of volume states that the volumetric rate of wire entering a die must be the same as that exiting. Because the cross-sectional area is reduced during drawing, it is necessary that a wire must increase in speed for the same volumetric rate of material to enter and exit the die. Volumetric rate is defined as the cross-sectional area of the wire multiplied by the wire velocity. This can be expressed mathematically as:

$$V_i \frac{3.14159 \times d_i^2}{4} = V_f \frac{3.14159 \times d_f^2}{4} \quad \text{Eq. (1)}$$

where  $V_i$  and  $V_f$  represent the wire velocities (feet or meters per minute) and  $d_i$  and  $d_f$  are the wire diameters (inches or millimeters) entering and exiting the die, respectively. For circular wire, Equation 1 can be simplified and reduced to:

$$V_i d_i^2 = V_f d_f^2 \quad \text{Eq. (2)}$$

In multi-pass drawing, wire speed exiting each die must increase so that the volumetric rate of metal flow is equal at all dies. Therefore, capstans, having an angular velocity equal to the exiting wire speed, are used to pull the wire through the die after each reduction. If this is not done, the wire will break due to unequal wire tension between dies. Because the volumetric rate must be the same at all points, wire velocity can be calculated at any intermediate stand once the incoming wire speed at the first stand is known. As an example, consider a 0.100-in. (2.5 mm) wire paid off from a spool at 1,200 feet per minute and reduced to 0.090 in. (2.286 mm) by using two passes. The velocity of the wire as it exits the last die can then be calculated by using Equation 2a as follows:

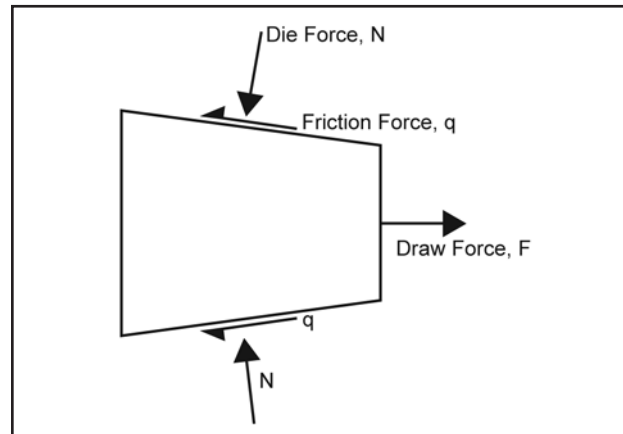
$$V_f = \frac{V_i d_i^2}{d_f^2} = \frac{1200 * 0.100^2}{0.090^2} = 1,481 \text{ feet per minute} \quad \text{Eq. (2a)}$$

Wire diameter increases as drawing dies wear in actual production; therefore, based on constancy of volume, wire speed will decrease as the dies increase in size. If the linear speed of the pulling capstan is matched to the wire size of a new die, capstan speed will be faster than the wire speed as the wire diameter increases. This increased capstan speed will apply high tensile stress on the wire, often breaking the wire. Therefore, capstans in multi-pass drawing machines are designed so that the wire slips on the capstan as the dies wear and the wire speed decreases (see Chapter 13). Slip is facilitated by limiting the number of wraps around the pulling capstan and wetting the wire and capstan surfaces with drawing lubricant.

### ***Forces and Energy in Wiredrawing***

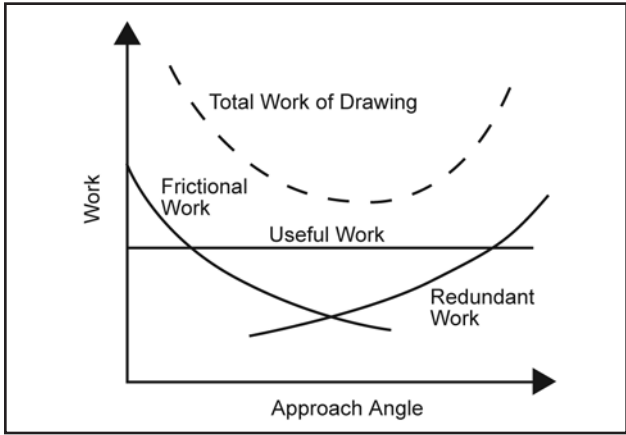
Although it may seem that the forces and power in wiredrawing could be analyzed by using simple tension, deformation conditions in wire are, in fact, far more complex due to compressive and drag forces generated by the die surface. A free body diagram of the forces acting on a wire is shown in Figure 1. Draw force,  $F$ , represents the total force that must be applied at the die block to overcome friction at the die surface and resistance of the deforming material. Because the draw force is being transmitted by unsupported material, the draw force must be limited to prevent any plastic deformation from occurring outside of the die. Thus, yield stress of the drawn wire rep-

resents an upper limit to the allowable draw stress. Accepted drawing practice normally limits draw stress to 60% of the yield strength of the drawn wire. Draw stress is found by dividing the draw force by the cross-sectional area of the drawn wire.

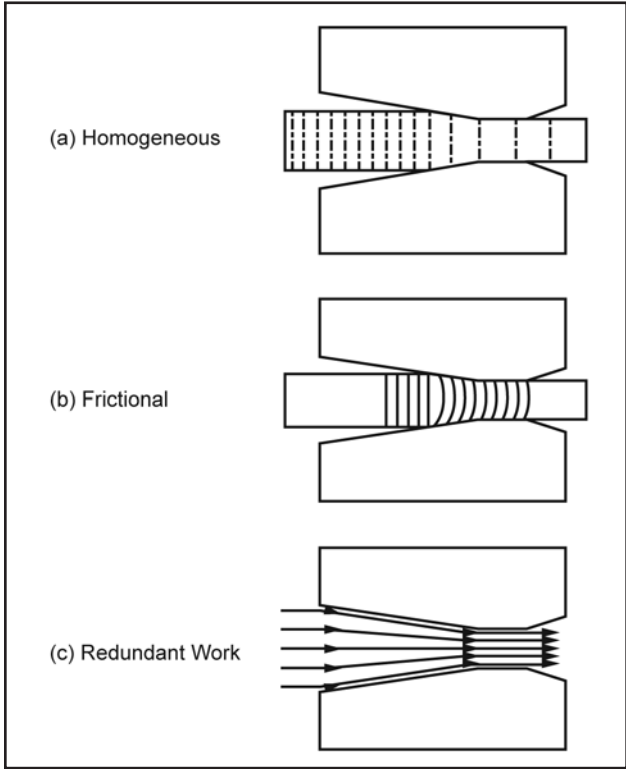


**Fig. 1. Free body diagram showing the primary forces operating in wire drawing.**

While it would appear that the work or energy consumed at a given draw stand is dictated by the material and reduction taken, the actual amount needed is considerably higher in practice. This is the result of inefficiencies that exist during deformation, which are primarily governed by the approach angle. Such inefficiencies do not make any useful contributions in reducing the cross-sectional area and generally serve only to increase energy requirements and adversely influence wire quality. The total work consumed at a draw stand can be partitioned into three components (see Fig. 2). These are: (a) useful (homogeneous) work required to reduce the cross section, (b) work required to overcome frictional resistance, and (c) redundant (inhomogeneous) work required to change the flow direction (see Fig. 3). Homogeneous work is determined by drafting (reduction), and is essentially independent of the approach angle. Friction and redundant work, on the other hand, are closely coupled to die geometry and have an opposite effect as the approach angle is changed. Under normal drawing conditions, typical losses are on the order of 20% for frictional work and 12% for redundant work.<sup>1</sup>



**Fig. 2. Components of work that operate during wire drawing.**



**Fig. 3. Illustration of (a) homogeneous, (b) frictional, and (c) redundant work in wire drawing.**

Redundant work and frictional work have adverse effects on wire properties in addition to increasing the energy needed for drawing. One consequence is that mechanical properties will not be homogeneous across the wire cross section. Because redundant and frictional deformations are concentrated near the wire surface, higher levels of strain hardening will result in the surface and near-surface layers (analogous to temper rolling) and will be greater than the strain that results from cross section reduction. This strain gradient can be verified easily by performing a hardness survey on a transverse section of cold drawn wire. Also, redundant deformation has an adverse effect on ductility, and this is clearly shown by Caddell and Atkins.<sup>2</sup> Their results showed that equal yield strengths were obtained at far lower strains for drawn stainless steel rod than for rod deformed in uniaxial tension. For example, to achieve yield strength of approximately 90 ksi (620 MPa), a rod only needed to be drawn to a true strain of 0.090, whereas the same material stretched in uniaxial tension required a true strain of 0.185.

Ductility is inversely related to strain; therefore, redundant deformation also acts to limit the number of passes and maximum reduction that can be taken prior to annealing.<sup>3</sup> Even if this does not lead to problems in drawing, the resultant loss in ductility can lead to fracturing in subsequent forming processes such as bending and cold heading.

### ***Effect of Friction***

Layers at the wire surface will not only undergo a change in cross section, but they will also deform in shear because of drag presented by the die surface (see Fig. 3b). Even for highly polished die surfaces and hydrodynamic lubrication, a certain amount of frictional work will be present. Frictional work dominates at low die angles where surface drag is increased as a result of higher contact length in the approach zone for a given reduction. Frictional work can be decreased by using a larger approach angle and, to a lesser extent, by improving lubrication or die surface condition. Although friction forces are also related to die load, normally little effort is made to control friction by limiting reduction since this would require additional stands. Instead, normal practice is to optimize approach angle and lubrication effectiveness.

The effect of friction is most conveniently quantified by using the Coulomb coefficient of friction usually represented by the Greek

symbol  $\mu$  ( $\mu$ ). The actual value of  $\mu$  depends on the surface condition of the die and lubrication used. Its exact value can be obtained experimentally by using the split die technique proposed by McClellan.<sup>4</sup> In practice,  $\mu$  normally ranges from 0.01 to 0.07 for dry drawing, and 0.08 to 0.15 for wet drawing.<sup>5</sup> In addition to surface condition and lubrication, coefficient of friction is inversely related to drawing speed. An experimental investigation of single-hole drawing by Ranger,<sup>6</sup> and later by Fowler,<sup>7</sup> showed that coefficient of friction dropped significantly as drawing speed increased.

### ***Redundant Deformation***

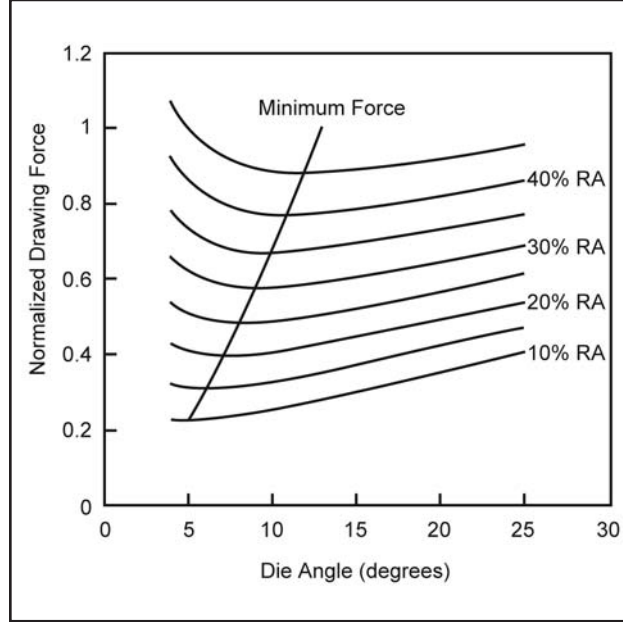
As wire enters the approach zone of a drawing die, material layers near the surface will undergo deformation due to the reduction in area and change direction of flow, i.e., bending to conform to the direction change going from the approach zone into the bearing zone of the die (represented by using flow lines in Figure 3c. Redundant deformation, like frictional deformation, will not be evenly distributed over the wire and will be at maximum at the surface with a corresponding increase in hardness. Redundant deformation is promoted by larger die angles since material further away from the centerline will undergo a sharper change in direction than the material near the centerline and will experience higher levels of distortion.

Based on split wire and X-ray diffraction studies, redundant deformation influences the level of residual stress in drawn wire. As the approach angle is increased, the deformation gradient between the surface and centerline also increases. This leads to progressively higher tensile stresses at the surface and compression stresses at the core. The reverse effect occurs during drawing, and center bursts can develop due to the high levels of tensile stresses generated in the core of the wire.

### ***Optimum Die Angle***

Selection of the proper die angle is crucial for the success of any wire drawing operation. Based on the fact that frictional work increases with *decreasing* die angle and redundant work increases with *increasing* die angle, an optimum approach angle should exist—one which minimizes both frictional and redundant work and, as a consequence, the drawing force. A number of investigators have confirmed that a balance between frictional and redundant work can be achieved through proper selection of the die angle. This effect is illustrated in

Figure 4. In addition to minimizing force requirements, the optimum die angle will also provide improved surface quality and finish.<sup>8</sup>



**Fig. 4. Optimum die angle, which minimizes frictional and redundant work as a die angle function for various reductions.<sup>5</sup>**

### ***Delta Factor***

The geometry of the working part (approach zone) of a die is a key factor in wire drawing. This geometry can be defined by the delta factor ( $\Delta$ ), which is the ratio of the circular arc spanning the mid-points of the die face to the length of contact between wire and die.<sup>5</sup> For conical dies, the  $\Delta$  factor is:

$$\Delta = \sin \alpha \left( \frac{D_1 + D_2}{D_1 - D_2} \right) \quad \text{Eq. (3a)}$$

where  $2\alpha$  is the included approach angle ( $\alpha$  is the approach semi-angle),  $D_1$  is the initial wire diameter, and  $D_2$  is the final wire diameter. For small approach semi-angles,  $\sin \alpha = \alpha$  in radians, and by multiplying the right side of Equation (3a) by  $(D_1 + D_2)/(D_1 + D_2)$



and substituting reduction in area  $[r = 1 - (D_2/D_1)^2]$  in place of the initial and final wire diameters,  $\Delta$  can be written as:<sup>9</sup>

$$\Delta = \frac{\alpha}{r} \left[ 1 + \sqrt{1 - r} \right]^2 \quad \text{Eq. (3b)}$$

Low  $\Delta$  values (small semi-angle or higher reduction in area) indicate larger friction effects and surface heating due to longer wire contact in the approach zone. Higher values of  $\Delta$  (large semi-angle or lower reduction in area) are indicative of increased levels of redundant deformation and surface hardening due to excessive direction change during flow through the die. Large  $\Delta$  often results in a greater tendency toward void formation and center bursting. Representative values of  $\Delta$  for a range of die semi-angles and reductions are given in Table 1. Delta values of 1.50 perform well in many commercial drawing operations; delta factors in excess of 3.0 should be avoided in general.

**Table 1. Delta parameter values for various approach semi-angles and reductions in wiredrawing.**

	Percent Reduction in Area							
	5	10	15	20	25	30	35	40
Semi-Angle (degrees)								
2	2.72	1.33	0.86	0.63	0.49	0.39	0.33	0.27
4	5.44	2.65	1.72	1.25	0.97	0.78	0.65	0.55
6	8.17	3.98	2.58	1.88	1.46	1.18	0.98	0.82
8	10.89	5.30	3.44	2.51	1.94	1.57	1.30	1.10
10	13.61	6.63	4.30	3.13	2.43	1.96	1.63	1.37
12	16.33	7.95	5.16	3.76	2.92	2.35	1.95	1.65
14	19.06	9.28	6.02	4.38	3.40	2.75	2.28	1.92
16	21.78	10.60	6.88	5.01	3.89	3.14	2.60	2.20
18	24.50	11.93	7.74	5.64	4.38	3.53	2.93	2.47
20	27.22	13.26	8.60	6.26	4.86	3.92	3.25	2.75

### *Drawing Force Calculation*

Numerous equations have been proposed to predict drawing force, though many of these calculations involve the use of empirical constants and/or lengthy calculations. Quite often there is a simpler equation to estimate the force that is needed. However, it should be noted that equations based only on homogeneous deformation should not be used as frictional work and redundant deformation have a significant effect and will seriously underestimate drawing

force if not included. Frictional work and redundant work are normally lumped together in a single efficiency term rather than included as separate terms in force calculations. A value of 60% has been found to provide acceptable results in ferrous drawing calculations. The following equation suggested by the Ferrous Committee<sup>10</sup> provides acceptable accuracy:

$$F_i = 1.6 (TS_{i-1} = TS_i) \left[ \frac{(3.14159)d_i^2}{4} \right] \ln \frac{d_{i-1}}{d_i} \quad \text{Eq. (4)}$$

where  $TS_{i-1}$  is the tensile strength of the wire entering the die at the  $i$ th stand and  $TS_i$  is the tensile strength of the drawn wire and  $d_{i-1}$  and  $d_i$  are the corresponding wire diameters. It should be noted that tensile strength is an engineering stress.

While many multi-hole processes are designed for a constant reduction at each stand, often it is preferable to achieve equal power consumption for each pass instead. Once drawing force is known, power can be obtained by multiplying drawing force ( $F_i$ , lbs.-force) and exit velocity ( $V_i$ , feet per minute), and then dividing the result by a factor of 33,000 to make the proper conversion to horsepower:

$$Hp_i = \frac{F_i V_i}{33,000} \quad \text{Eq. (5)}$$

### ***Advanced Drawing Force Calculation***

A more complex calculation, but one that gives acceptable accuracy and permits the effects of friction, die angle, and back pull to be explicitly considered, was proposed by Sachs in 1927.<sup>11</sup> Based on Sach's analysis, drawing stress at an individual stand,  $\sigma_d$  can be calculated as:

$$\sigma_d = \sigma_{average} \left\{ \left[ \frac{1 + \Theta}{\Theta} \left( 1 - \frac{d_{i-1}^2}{d_i^2} \right) \right]^\Theta + \frac{\sigma_{backpull}}{\sigma_{average}} \left( \frac{d_{i-1}^2}{d_i^2} \right) \right\} \quad \text{Eq. (6)}$$

where:  $\Theta = \frac{\mu}{\tan \alpha}$

and  $\sigma_d$  is drawing stress,  $\sigma_{backpull}$  is the stress generated by any back-pull,  $\mu$  is the Coulomb coefficient of friction, and  $\alpha$  is the die semi-angle in degrees or radians. The average yield stress,  $\sigma_{average}$ , for a material that undergoes work hardening can be calculated by using the following relation:

$$\sigma_{average} = \frac{K\varepsilon^n}{1 + n} \quad \text{Eq. (7)}$$

$K$  and  $n$  are material constants used to calculate true stress and previously defined in Chapter 8.

Drawing stress,  $\sigma_\phi$  can then be used to calculate the maximum allowable drawing force in pounds or Newtons at an individual stand as follows:

$$F_{max} = 10.6 * \sigma_{draw} * \frac{\pi d_i^2}{4} \quad \text{Eq. (8)}$$

where:  $d_i$  is the wire diameter exiting the die.

### **Die Pressure**

Although die pressure is normally not a primary consideration in wire drawing, it does have a significant effect on die life. In general, die wear increases with pressure, and the average die pressure in psi or MPa can be estimated by using the  $\Delta$ -parameter.<sup>3</sup>

$$P_{average} = \sigma_{average} \left( \frac{\Delta}{4} + 0.6 \right) \quad \text{Eq. (9)}$$

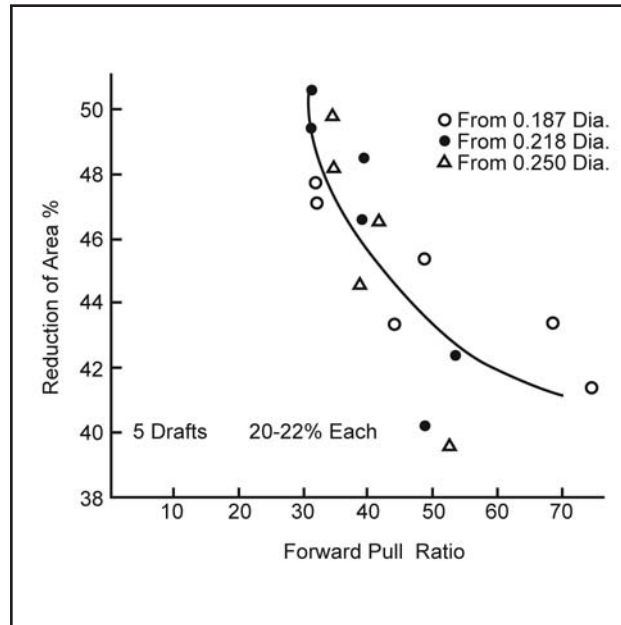
From Equation 9, it is apparent that lower die pressures and better die life can be achieved by using low values of  $\Delta$ -parameter corresponding to smaller approach angles and higher reductions per pass, which provide larger contact area in the approach zone. When a given drawing force is applied over a larger contact area, the resulting die pressure is decreased. However, a degree of caution is needed since increased contact area along the approach can promote frictional heating at the wire surface resulting in lubricant breakdown.<sup>3</sup>

### ***Effect of Back Pull***

It has been known for many years that intentionally applying back pull can help to produce improved die life and dimensional control by reducing die load. Lewis and Godfrey<sup>12</sup> studied the effect of back pull on die load, and their results indicated that up to a 30% reduction is possible. A second benefit of using back pull is that lower surface temperatures can be obtained as the reduced die load also acts to reduce the frictional drag. Back pull is normally present to some extent in any multi-hole process, as the drawing force in the preceding stand tends to act as a back pull in the next draw stand. A second source of back pull results from the use of capstans.

In practice, however, the intentional use of back pull to improve die life and to reduce temperature is rarely used, as the disadvantages more than offset any potential gains. As the amount of back pull is increased, drawing force must necessarily increase for a given reduction to satisfy requirements for force equilibrium. Additionally, there is an upper limit to the amount of back pull that can be applied. As the amount of back pull is increased and begins to approach the level of the drawing force, die load will approach zero. At this point, the wire will deform by stretching in simple tension, rather than by contact with the drawing die. At sufficiently high levels of back pull, deformation can extend outside of the die, resulting in undersized or broken wires.<sup>5</sup>

An additional effect of back pull is that the axial component of stress will be increasingly tensile over the wire cross section, which forms internal voids and reduces overall wire ductility. In their study of back pull, Lewis and Godfrey<sup>12</sup> observed that the reduction of area for drawn high carbon wire was reduced by 10% during tensile testing, and a reduction in the number of bends obtained during bend testing was also noted. This loss of ductility ultimately is detrimental as it requires the use of smaller drafts at each stand as well as an attendant increase in the number of stands needed for a given total reduction. However, if properly controlled, back pull can yield a more homogeneous strain distribution in the wire due to a more uniform axial stress distribution. Simons verified this for high carbon steel wire.<sup>13</sup>



**Fig. 5. The effect of increasing back pull on ductility.<sup>12</sup>**

### *Thermal Effects*

Temperature control is a critical issue in wire drawing, and it often proves to be the limiting factor with respect to productivity in multi-hole processes. In the absence of any cooling, the temperature increase in commercial drawing operations can easily exceed several hundred degrees Fahrenheit. If temperature is not controlled, the resulting heat gain can adversely impact wire properties, lubrication effectiveness, and surface condition, as well as accelerate die wear. Thermal management is particularly important for high carbon wire where the higher yield stress generates more heat, while the tendency for embrittlement from strain-aging is also accelerated at higher temperatures.<sup>1</sup> Not surprisingly, heat effects will vary over the wire cross section, being most pronounced at the surface as a consequence of frictional work and redundant deformation. Furthermore, this can also promote unfavorable residual stress patterns due to the resulting non-uniform thermal expansion.

While it is well known that wire temperature increases with drawing speed, adiabatic heating in the wire is actually independent of

velocity and several investigations have confirmed this.<sup>1,7</sup> Unless the wire is cooled to ambient temperature after each stand, heat will accumulate and wire temperature at each subsequent die inlet will rise. In single-hole processes, however, the resulting temperature rise is normally too low to have an appreciable effect. In multi-hole processes, heat accumulates at each stand and the temperature rise may become sufficiently high to affect drawability and wire properties, particularly at drawing speeds that exceed of 300 feet per minute.<sup>14</sup>

### ***Heat Rise from Work of Deformation***

Heat is generated primarily by work of deformation (reduction) and sliding (friction) at the die surface. Adiabatic heating is proportional to the amount of deformation; therefore, heating and temperatures are higher at the wire surface than at the centerline. Although an exact calculation would require complex mathematics, a reasonable estimate of the temperature rise ( $\Delta T$ ) in degrees Fahrenheit in the wire can be obtained by using an empirical equation proposed by Wilson:<sup>14</sup>

$$\Delta T = \frac{1.069 \times 10^4 \times F}{C \times A_f \times \rho} \quad \text{Eq. (10)}$$

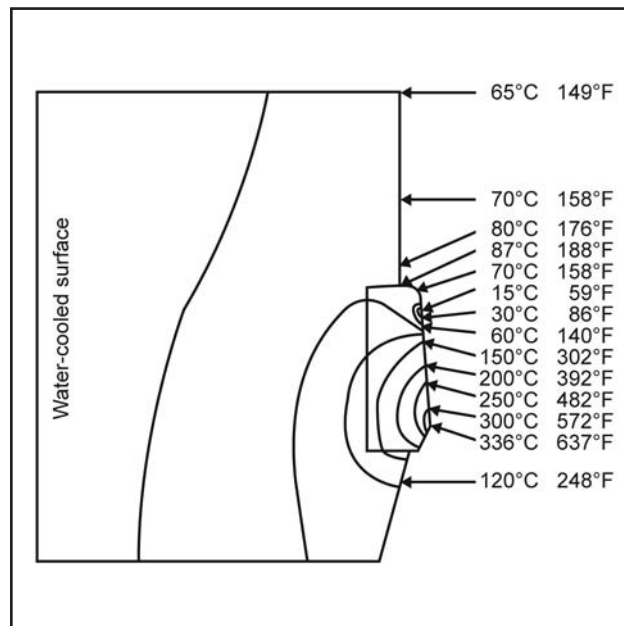
where:  $F$  is the die pull (lbs.-force),  $C$  is specific heat capacity of steel (cal per gm per °C = 0.1153 at 100°C),  $A_f$  is final wire cross-sectional area (in.<sup>2</sup>), and  $\rho$  is density of steel (lbs./in.<sup>3</sup>).

As seen in Equation 10, temperature rise is proportional to the amount of deformation. Thus, it is to be expected that the hottest location in the die will be at the junction of the approach and bearing zones where deformation is the greatest in the die and significant sliding has occurred in the approach zone. This has been confirmed in the classical study performed by Ranger (see Fig. 6).<sup>6</sup>

### ***Inter-pass Cooling***

Drawing dies can extract only a small amount of heat, so proper attention must be paid to inter-pass cooling, particularly at the latter reductions. While some of the heat is transferred to the die, most stays in the wire, and attempts to use die cooling to reduce wire temperature have proved largely unsuccessful. Various studies on the effectiveness of die cooling found that a die typically removes no more than 5–20% of the heat generated in the wire. This is due to the

fact that a given area of wire is in contact with the die surface for only thousandths of a second. For example, when a 0.080-in. (2.0 mm) mild steel wire was drawn through dies with conventional cooling, the heat extracted was 7% at 200 ft./min., 3% at 1000 ft./min., and 1% at 5000 ft./min. Even though the die is expected to remove only minimal heat from the wire, die temperatures cannot be overlooked, and cooling of the die case is often necessary. This is particularly true when carbide inserts are being used in a steel casing due to the large difference in coefficients of thermal expansion (see Chapter 14).



**Fig. 6. Experimental temperature field for a single-hole drawing process.<sup>6</sup>**

A good rule of thumb for temperature increase per pass in dry drawing (other than the first die) is 140–176°F (60–80°C) for mild steel and 212–320°F (100–160°C) for high carbon steel. These values are halved for wet drawing. Godfrey reported a decrease in temperature of 104°F (40°C) when applying heavy back pull.<sup>12</sup>

Three modes of wire cooling are used in commercial operations:

- Direct Cooling—Water of coolant is sprayed onto wire exiting the die or on the take-up capstan.

- Indirect Cooling—Water or coolant is sprayed onto the die casing or is circulated on the inside on the die casing or take-up block.
- Air Blast—Forced air impinges on wire on the block or capstan.

Inter-pass cooling often employs direct water cooling on the wire exiting a drawing die, and using the residual heat in the wire to remove the last of the water by evaporation. Direct cooling combined with internal block cooling can bring the wire temperature to below 250°F (120°C), which is a reasonable starting temperature for the next reduction. Kobe direct water-cooling, British Iron & Steel Research Association narrow gap capstans, spray (micro-mist) cooling, aluminum blocks with thinner walls and internal fins with rapid counter-flow water circulation, and composite outer walls (steel plus brass) of blocks are used for inter-pass cooling in many wiredrawing operations. It is important to prevent oxidation and fouling of internal surfaces of the blocks to maintain good heat transfer between the hot wire and cooling water.

The effective means of cooling drawn wire are:

- Ensure that wire enters die as cold as practical.
- Avoid heavy drafting.
- Employ the best possible lubrication.
- Consider using back pull.
- Increase time intervals between drafts.
- Increase number of wraps on the block.
- Increase block diameter.

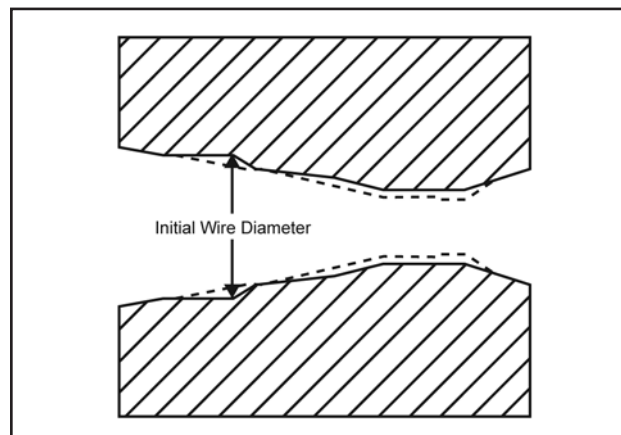
### *Die Life and Wear*

Two primary variables that control die life in any metal forming operation are pressure and temperature. Pressure acting on the die in wiredrawing is much lower than found in other cold forming operations, such as cold heading and backward extrusion. Consequently, temperature is often a far more critical factor in controlling die life. Although it would seem logical that wear would occur uniformly along the approach zone, this is not the case in practice. Maximum wear (measured in volume loss) normally occurs at the point at which the wire initially contacts the die. There, a deep annular crater is



formed, which is referred to as a “wear ring” (see Fig. 7).<sup>15</sup> Ringing results when the plane of impingement of wire on the die oscillates about a mean position because of irregularities of size and vibration of the wire. As a consequence, a narrow zone of the die bore is subjected to a cyclic load with eventual subcutaneous failure by fatigue.

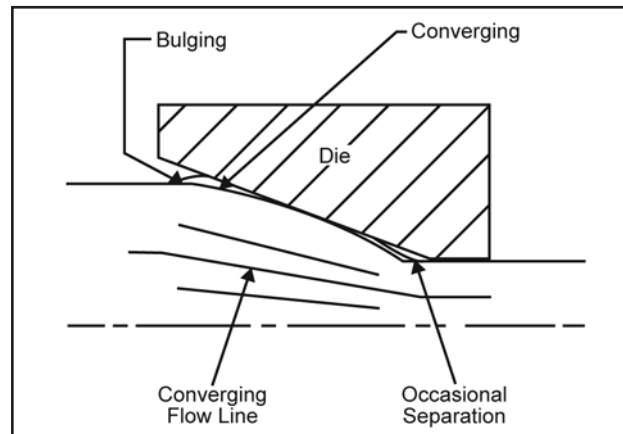
Once a wear ring develops, deformation may occur prior to the contact point in the drawing die. This is called “bulging” and results from backup or upsetting of near-surface regions of the wire as contact is made at the wear ring location in the die. Bulging occurring at the initial point of contact in the die throat limits lubricant entry into the die and accelerates die wear (see Fig. 8).<sup>16</sup> Lesser amounts of wear occur along the contact length of the approach zone, although here too wear is not uniform and often results in an oval rather than a circular wear surface.<sup>5,15</sup>



**Fig. 7. Wear formed by ringing in a drawing die.<sup>15</sup>**

Wires sliding against the working area of a drawing die cause die wear so that wear depends on the surface area of wire, and consequently the length of wire, passing through a drawing die. Often, die life is measured in terms of weight of wire drawn or time of drawing; however, such measures should be converted to length of wire drawn to get a fundamental indication of die wear. Therefore, a practical measure of die life is the mean length of wire drawn per unit increase in die diameter (typically 0.001 in.). Typical mean die life, measured in miles of wire drawn per mil (0.001 in.) increase in die size, for several die materials is listed in Table 2. As a general rule, materials hav-

ing a high yield strength and melting point are more resistant to wear. However, recent studies have demonstrated that die hardness does not control die wear, i.e., increasing hardness of die material does not lead to a substantial increase in die life.<sup>17</sup> Research on predicting die life that is based on physical properties of wire and drawing dies has not been successful to date. Additional work must be done before results can be applied to commercial drawing processes.



**Fig. 8. Wire bulging that occurs at the throat in drawing dies.<sup>16</sup>**

### *Non-Traditional Drawing Methods*

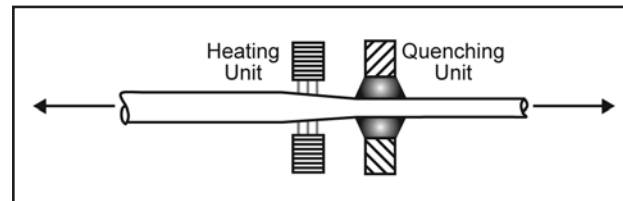
Tapered dies have been the mainstay in wiredrawing for more than 1,800 years; however, numerous research and development efforts focused on alternative geometries (concave, sigmoidal, etc.) to overcome the inherent limitations that exist in conical die technology (see Chapter 14). While many of these novel methods offer interesting possibilities, practical difficulties have prevented many from achieving a high level of commercial acceptance.

**Table 2. Die life for various common die materials.<sup>5</sup>**

Die Material	Average Die Life (miles/0.001 inch diameter increase)
Mild Steel	0.25 – 1
High Carbon Steel	15 – 40
Tungsten Carbide	50 – 200
Synthetic Diamond	1 – 8 X 10 <sup>6</sup>

### ***Die-less Wiredrawing***

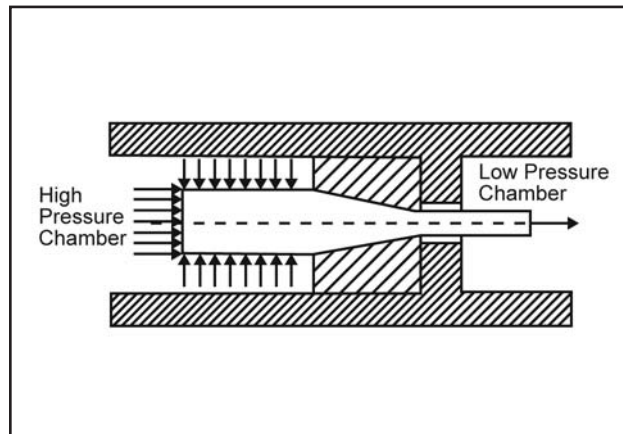
As the name implies, the principle behind die-less wiredrawing (see Fig. 9) involves heating and then stretching the wire in simple tension through differential capstan velocities, rather than reducing the cross section by pulling it through a sequence of dies. Normally, the wire must be rapidly cooled immediately after exiting the heating zone to strengthen the reduced area and to suppress necking. Applied tensile force determines the final wire diameter, so process conditions must be monitored and controlled rigorously. The purported advantages of this process are: a broad range of wire diameters can be prepared in a single pass from a small number of starting rod sizes, minimal labor is required to operate the mill, and the need for large die inventories is eliminated. It is envisioned that this process could lead to flexible “mini-mills” that could serve the needs of regional customers with greatly reduced physical plant requirements.<sup>18</sup> While several attempts have been made to commercialize the process, a number of concerns have been expressed with regard to the equipment cost and ability to control finish diameter.<sup>18</sup>



**Fig. 9. Basic principle involved in die-less wire-drawing process.<sup>18</sup>**

While the maximum reduction is limited when wire is drawn through a conventional die, no such limit exists in extrusion. Experimental work during the 1960s and 1970s showed large reductions were possible in a single pass by using hydrostatic wire extrusion. Even though its potential has never been realized in commercial drawing practice, this technology was demonstrated at Western Electric where 5/16 in. (7.9 mm) diameter copper and aluminum rods were successfully reduced by 400:1 and 150:1, respectively, at speeds of up to 12,000 ft. per min. (61 m/s).<sup>19</sup> An advantage of the process is that heating is not required (see Fig. 10). Bridgman pioneered much of this work in the 1920s.<sup>20</sup> Bridgman discovered that specimens subjected to superimposed hydrostatic (compressive) stresses of

up to -450 ksi (-3104 MPa) during tensile testing demonstrated greatly enhanced ductility. This is due to the superimposed compressive stress suppressing void formation and separation at interface boundaries between the matrix and second phase particles. The superimposed hydrostatic stress does not affect fracture resulting from tensile instabilities, such as necking, which are the primary causes of failure in ferrous wiredrawing and making it necessary to extrude rather than to pull material through the die.<sup>21</sup> This is achieved by reducing the workpiece (rod) while simultaneously subjecting it to pressurized fluids at a mean pressure on the order of 200,000–300,000 psi. Significant disadvantages of the process are: difficulties associated with feeding rod on a continuous basis, ensuring high compressive pressures in the extrusion chamber, maintaining adequate lubrication, and equipment complexity.



**Fig. 10. Illustration of the basic principles involved in hydrostatic wiredrawing.**

### ***Ultrasonically Assisted Drawing***

The advantages of using ultrasonic oscillations in wiredrawing were recognized for many years, and research actively began in the early 1960s. However, while successful applications were demonstrated, ultrasound had only limited acceptance in the wire industry, and it is now used mainly in cleaning and materials joining to a limited extent. A probable reason for this limited usage is that many ultrasonic applications focused on conventional engineering alloys where workability and mechanical properties were not limiting fac-

tors and the alloys could be drawn economically by using conventional practices.

A number of researchers<sup>22-25</sup> studied the effect of ultrasonic vibration in wire and tube drawing using steel, aluminum, and copper alloys. Benefits documented in these studies included reduced drawing force and increased reduction per pass. In most investigations, the drawing die oscillated in the longitudinal direction (parallel to the drawing direction). While researchers have observed substantial reduction in drawing force, there is disagreement among them as to whether force reduction resulted from reduced friction, reduction in yield stress of the wire, or a reduction in force from super-positioning of the ultrasonic waves with the applied drawing stress. Excessive levels of insonation\* can produce undesirable results, including fracture.<sup>22,24,26</sup> However, most researchers have reported that moderate levels of insonation superimposed during deformation resulted in properties equal to or somewhat better than un-insonated materials.

### ***Computer-aided Analysis of Wiredrawing***

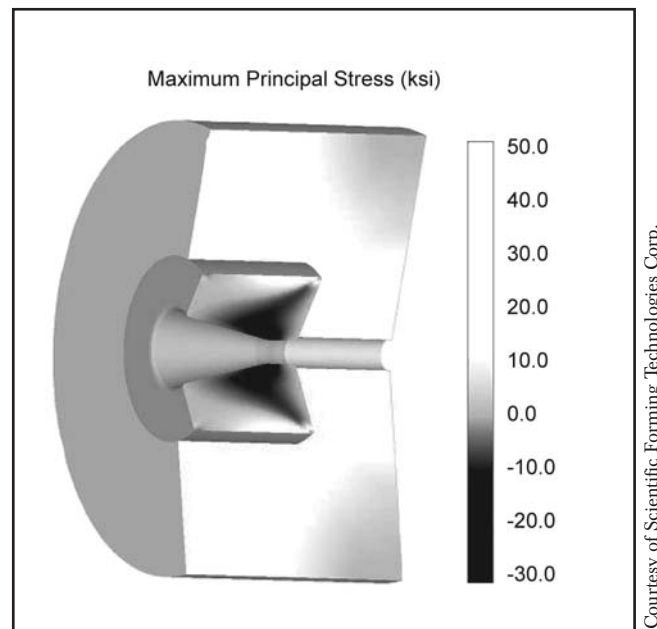
Numerous closed form equations have been developed to model the mechanics of wiredrawing. Due to the complexity of the mathematics involved, only a limited amount of information can be gained from such models. However, much of this difficulty has been eliminated with the advent of the modern computer. With the introduction of user-friendly software and faster computers, computer-based analysis of wiredrawing has become increasingly common in recent years. By using computer-based analysis, sophisticated mathematical models that incorporate thermal and mechanical effects can be developed easily to analyze a large number of different conditions at relatively little cost, and often with minimal reliance on physical experimentation. When combined with advanced computer graphics capabilities, such models can provide unprecedented insight regarding stress, strain, and temperature fields as a function of time. Provided appropriate input data are available, computer models also can be used to predict the onset of defects, to predict microstructural changes, and to evaluate process conditions during wiredrawing, often without resorting to costly plant trials.

Details of the mathematics of the finite element methods, which tend to be rather complex, are well established and covered in detail

in numerous books on the topic. Only an overview is provided here to acquaint the reader with a basic understanding of the method.

The finite element method is a numerical approach to problem solving that relies on dividing a complicated problem into a set of smaller more simplified problems that are easily solved. Due to the large number and complexity of the equations used to represent the workpiece, a computer must be used to solve the problem. When all the individual solutions are re-combined, they represent the overall problem solution.

There are three individual steps involved in computer modeling—pre-processing, simulation, and post-processing. In the pre-processing stage, a graphical user interface supplying the appropriate geometric, material, and other physical properties that represent the process characteristics develops a mathematical description of the process. During the simulation stage, a mathematical solution is determined for sequential points in time by the computer and is normally performed independently of any user activity. Once the simulation has been executed, results can be viewed graphically and specific variables or behavior of interest can be analyzed (see Fig. 11).



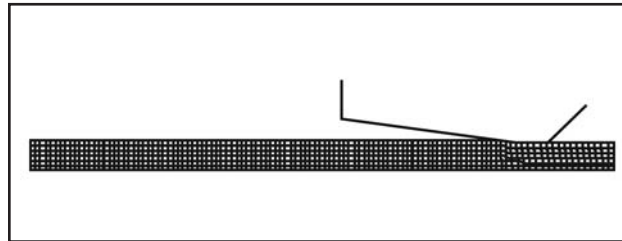
**Fig. 11. Three-dimensional graphical representation of principal stress (in ksi) in a wiredrawing die.**

In finite element modeling of a wiredrawing process, the wire is normally considered to be a deformable plastic body that can undergo a change in shape; the die is treated as an elastic body that deforms very little or as a rigid body where deformation is ignored. Unless die deflection or stresses are analyzed in an isothermal analysis, considerable simplification of the model is achieved by treating the die as a rigid body, and the die surface is then effectively reduced to a simple mathematical boundary condition. Each object in the model that is assumed to deform is first discretely distinguished by dividing the interior into a large number of simple geometric entities termed “elements.” However, if a thermal analysis is performed, rigid objects also must be discretely identified. Each element is interconnected with adjacent elements at points that are termed “nodes” and are used to describe the behavior of a small portion of the object. When all elements are fully assembled, they appear as a grid. Nodes and elements also store values calculated at various intervals during the simulation. Model accuracy and resolution is heavily dependent on the number of elements and nodes used. If steep property gradients or rapidly changing behaviors are anticipated, a larger number of elements and nodes (i.e., a dense mesh) should be used.

Each node actually represents a set of simultaneous equations in matrix form that are solved subject to a number of constraints and boundary conditions to determine the approximate displacement or velocity at that point. The number of equations at each node is based on the allowable directions of movement or degrees of freedom specified in the model. Displacement and velocity are then used to calculate strain and/or strain rate, which in turn, are used to calculate stress through the use of a “stiffness matrix.” Because deformation is non-linear, it is not possible to obtain a solution in one step; therefore, the process must be subdivided and solved sequentially at different points corresponding to real or actual process time until the desired point is reached. Each individual point in time for which a solution was calculated is termed a time-step. Normally each time step is on the order of several thousandths of a second. If thermal effects are also analyzed, the solution procedure is staggered, i.e., first the deformation solution is found and then the thermal solution is solved and used to update the deformation conditions prior to solving the next time step.

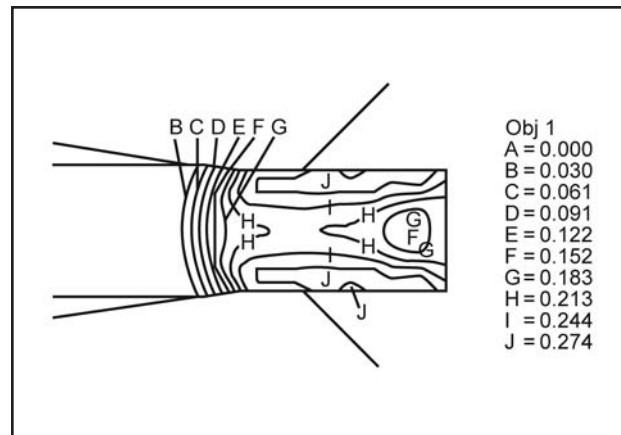
An example of a simple two-dimensional isothermal computer simulation is shown in Figures 12 to 14. Figure 12 shows a graphical

representation of the wiredrawing process after the wire has been partially drawn, and only the workpiece (wire) is assumed to undergo deformation. Because die deflection was not analyzed, only the boundary representing the die surface is shown. Furthermore, due to the process symmetry, only half of the process is modeled and a boundary condition (not shown) is imposed along the centerline resulting in considerable simplification.



**Fig. 12. Finite element representation of the wiredrawing process. Due to axisymmetry, only one-half of the process is shown.**

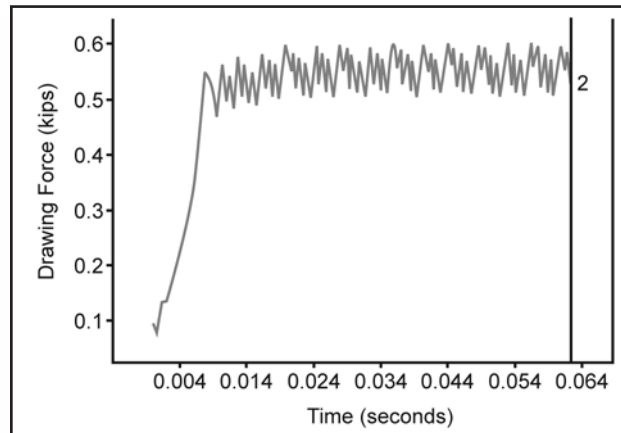
Figure 13 shows the simulated strain fields in the leading region of the wire after 0.06 seconds using a drawing speed of 49 ft./min. (15 m/min.). It can be seen that a gradient exists and that strain is not uniform over the cross section.



**Fig. 13. Effective strain distribution in a drawn wire obtained by using finite element simulation.**



Drawing force as a function of time is shown in Figure 14. The change in drawing force as the wire enters the die and then achieves a steady-state value once the leading edge exited the die can be readily discerned. The benefit of the graphical representation is that the overall behavior of a specific variable can be visualized, and excessive levels, indicative of process problems, easily recognized. Furthermore, because the model can store data from previous time steps, an engineer can trace the process behavior over time and track the development of any variable or process condition, which is often invaluable in determining root causes to problems. A final note is that deformation modeling could easily be extended to a multi-hole process by adding one or more dies to the existing model.<sup>27,28</sup>



**Fig. 14. Simulated drawing force generated by finite element simulation.**

### *References*

1. Flanders, N. A. and E. M. Alexander. "Analysis of Wire Temperature and Power Requirements on Multi-Pass Drawing Productivity," *Wire Journal International*, Vol. 12, No. 4, pp. 60–64, The Wire Association International, Inc., Guilford, Connecticut, 1979.
2. Caddell, R. M. and A. G. Atkins. "The Influence of Redundant Work When Drawing Rods through Conical Dies," *Journal of Engineering for Industry*, Vol. 90, pp. 411–419, 1968.

3. Wright, R. N. "Factors to Consider in Wire Die and Pass Schedule Design: Technical Paper MF77-960," p. 10, Society of Manufacturing Engineers, Dearborn, Michigan, 1977.
4. McClellan, G. D. S. "Some Friction Effects in Wire Drawing," *Journal of the Institute of Metals*, Vol. 81, No. , pp. 1-13, September 1952.
5. Wistreich, J. G. "The Fundamentals of Wire Drawing," *Metallurgical Reviews*, Vol. 3, No. 10, pp. 97-141, 1958.
6. Ranger, A. E. "An Electrical Analogue for Estimating Die Temperatures during Wire Drawing," *Journal of the Iron and Steel Institute*, Vol. 185, pp. 383-388, 1957.
7. Fowler, T. and P. R. Lancaster. "Factors Limiting Speed in Wire Drawing," *Wire Industry*, Vol. 50, No. 592, pp. 208-211, 1983.
8. *Drawing and Ironing*, in *Handbook of Metalforming*, ed. K. Lange, p. 14.27, McGraw-Hill Book Company, New York, 1985.
9. Wright, R. N. *Workability in Extrusion and Wire Drawing*, in *Workability Testing Techniques*, ed. G. E. Dieter, p. 255, ASM International, Materials Park, Ohio, 1984.
10. *Pocket Guide for Ferrous Drawing Practice*, Ferrous Drawing Committee: The Wire Association International, Inc., Guilford, Connecticut, 1988.
11. Sachs, O. A. and G. Hoffman. *Introduction to the Theory of Plasticity for Engineers*, pp. 178-186, McGraw-Hill Book Company, New York, 1953.
12. Lewis, D. and H. J. Godfrey. "Back Pull in Wire Drawing," *Wire & Wire Products*, Vol. 24, pp. 873-885, October 1949.
13. Simons, L. *Wire & Wire Products*, Vol. 13, pp. 441-443, 1938.
14. Wilson, N. A. "Cooling of Steel Wire During Continuous Drawing," *Wire & Wire Products*, Vol. 29, No. 10, pp. 1160-1169, October 1954.
15. Wistreich, J. G. "Ringing in Wire Drawing," *Journal of the Iron and Steel Institute*, Vol. 167, pp. 160-163, 1951.
16. Avitzur, B. *Handbook of Metal Forming Processes*, p. 79, Wiley, New York, New York, 1983.
17. Enghag, P. *Steel Wire Technology*, p. 163, Repro Orebro University, Orebro, Sweden, 2002.
18. Dixon, R. F. "Company Works to Develop Die-Less Drawing Process," *Wire Journal International*, Vol. 20, No. 10,

- pp. 25–26 and 28, The Wire Association International, Inc., Guilford, Connecticut, 1987.
19. Andrus, P. and G. Schmehl, “Continuous Hydrostatic Wire Extrusion,” Paper No. MF76-409, p. 16, Society of Manufacturing Engineers, Dearborn, Michigan, 1976.
  20. Bridgman, P. W. *Studies in Large Plastic Flow and Fracture*, McGraw-Hill Book Company, 1952.
  21. Alexander, J. M. “Hydrostatic Extrusion of Wires,” *Journal of the Institute of Metals*, Vol. 93, pp. 366–369, 1965.
  22. Pohlman, R. and E. Lehfeltdt, “Influence of Ultrasonic Vibration on Metallic Friction,” *Ultrasonics*, pp. 178–185, October 1966.
  23. Robinson, A. T, J. C. Connelly, and L. H. Stayton. “The Application of Ultrasonics in Wire Drawing,” *Wire and Wire Products*, Vol. 39, No. 12, pp. 1925–1931, December 1964.
  24. Schmid, E. “Plasticity of Insonated Metals,” *Transactions of the Japanese Institute of Metals*, Vol. 9, pp. 798–804, 1968.
  25. Winsper, C. E. and D. H. Sansome. “Fundamentals of Ultrasonic Wire Drawing,” *Journal of the Institute of Metals*, Vol. 97, pp. 274–280, September 1969.
  26. Kearns, T. F. “MPEP—the Metalworking Processes and Equipment Program,” *Metals Engineering Quarterly*, pp. 1–4, May 1964.
  27. Yoshida, K., R. Ido, and T. Denshi. “Effects of Back Tension and Drawing Direction on Wire Properties in Copper Wire Drawing,” Conference Proceedings, 71st Wire & Cable Technical Symposium, pp. 227–233, Atlanta, Georgia, The Wire Association International, Inc., Guilford, Connecticut, May, 2001.
  28. Shemenski, R. M., M. A. Foster, and J. Walters. “Finite Element Analysis of Die Geometry for Drawing Steel Wire,” Conference Proceedings, 74th Wire & Cable Technical Symposium, pp. 42–55, Cleveland, Ohio, The Wire Association International, Inc., Guilford, Connecticut, June, 2002.

#### *Notes*

\* insonation—application of ultrasonic energy