The Pressure Velocity (PV) Relationship for Lead Screws

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The Pressure Velocity (PV) factor is a key design parameter in the proper sizing and selection of lead screw assemblies that use polymer nuts. Although you will find it listed for most engineering polymers, PV is generally overlooked when considering nut load ratings. It is more commonly applied to radial bushing and slide applications. PV can define the performance envelope for a lead screw assembly by the product of pressure and velocity between nut and screw. Plastics have an intrinsic limiting PV rating while the PV of a system running under certain conditions can be calculated. Put simply, the more load applied to the lead screw assembly, the slower it must be turned to avoid exceeding the nut's PV limit. The reverse is also true, more speed, less available load capacity.

Plastics are assigned PV ratings by the compounder of the specific product. Some common compounded plastics are DuPont's Delrin® AF, Quadrant's Torlon®, and GE Plastics' LNP Lubriloy. The compounder is responsible for the formulation of resin and additives that are chosen. Additives are commonly included to improve structural and tribological properties. Compounders typically conduct PV testing using a disc of material sliding on a steel surface. By varying load and speed on the test specimen, the wear inflection point can be determined and hence the limiting PV for the material. While a base resin may have a certain PV rating, by adding lubricants and other compounds, that rating may be greatly enhanced. This provides the designer with considerable flexibility in achieving a suitable PV envelope for their application. It should be noted that test methods differ from company to company, so it is best to compare different plastics from a single compounder when selecting a material. As we will see, the system PV can also be addressed by modifying the geometry of the lead screw components.

Surprisingly, most designers simply look at the nut load rating when sizing their systems and ignore the impact of speed. This can lead to rapid and sudden failure. The primary modes of failure for lead screws are wear and PV. By designing within the PV envelope, failure is forced to occur as a result of wear.

Wear is a slower and more linear type of failure which can be accounted for in design.

The limiting PV for any given material can be represented on a PV Chart (see figure 1).

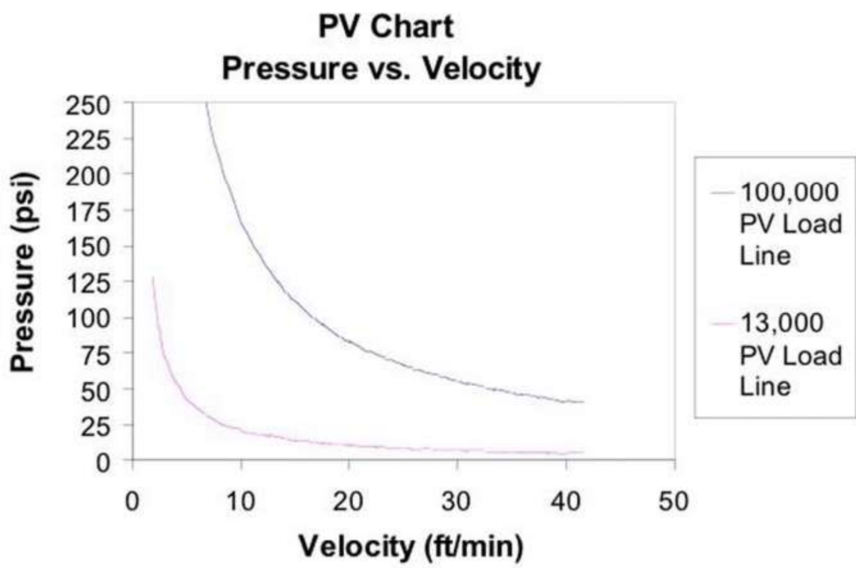

Figure 1

This is accomplished by setting the product of pressure and velocity equal to the material's PV limit (see equation 1). Pressure is defined as the axial force applied to the nut divided by it's projected bearing area and velocity as the sliding speed between the surfaces. By solving for pressure (or velocity), one can plot the curve over a desired range of velocities (or pressures). In order to prevent failure, the system PV must be held below the material PV curve.

In order to determine how the material's limiting PV relates to the system PV of a lead screw assembly, it is necessary to analyze its geometry. Start by calculating the projected area of engagement between the threads of a nut and screw by obtaining the helix length (equation 5). This is the imaginary line running around the thread at its pitch diameter where theoretical thread engagement occurs. By unwrapping the helix of the screw thread we can analyze it as a triangle with the hypotenuse representing the helix length for one rotation of thread (equation 4). The pitch diameter and lead of the thread are the base and height for the right triangle. Solving for the hypotenuse and multiplying by the number of thread turns in the nut and the number of thread starts we get the total helix length. This can be multiplied by the depth of thread engagement between nut and screw to calculate the area in contact between the two (equation 2). Surface velocity can be calculated by multiplying the helix length per turn by the speed of rotation (equation 3).

A complicating factor arises in practice. Due to the inherent stiffness of the polymer materials used for the nut, deflection occurs between the thread of the nut and screw (see figure 2).

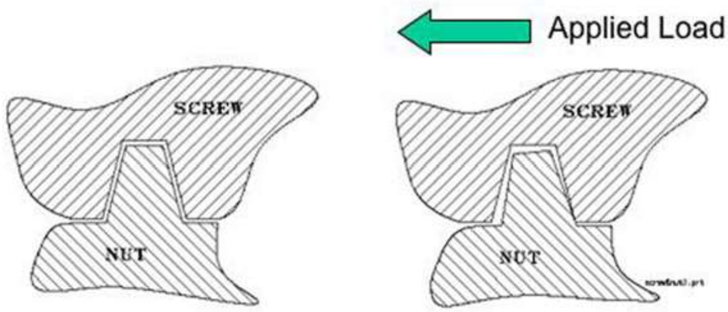

Figure 2

The deflection results in the thread of the nut rotating as in beam bending such that the contact patch between nut and screw is reduced. As this reduction occurs, the patch moves further and further up the flank of the screw thread until most of the load is carried near the major diameters (see figure 3).

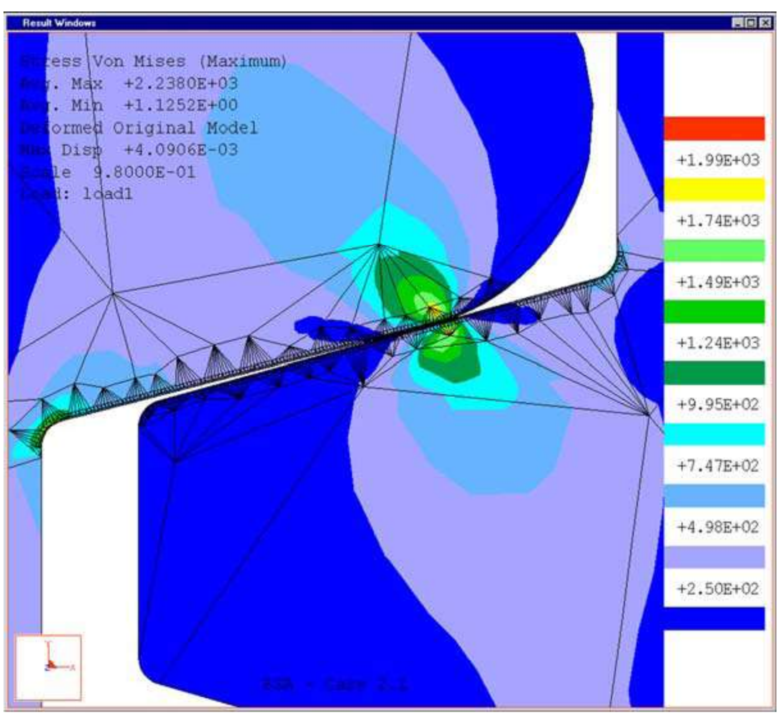

Figure 3

This has a negative effect on the pressure between the two parts under a given load. In practice it is difficult to calculate what this reduction in area will be. Unfortunately, the area decreases as the load increases, compounding the tendency for PV related failure and underscoring the need to stay within the performance envelope. To address this issue, a correction factor (C_f) is applied to the projected area. This factor normally ranges from about .75 to .25 as the loading increase from light to the full rated load capacity.

By calculating the helix length, determining the pressure and multiplying this by the surface velocity, a system PV can be calculated. Assure that units are either in psi ft/min or MPa m/s. This can be compared to the PV rating of the material. A factor of safety of 2 is recommended. It has been noted that when the system PV is more than ½ the limiting PV, the wear rate accelerates. Therefore, while sudden failure may not occur, the wear life of the system will be reduced.

Alternatively, one can plot a chart of Load vs. RPM or Linear Speed (of the nut). By dividing the pressure by the corrected contact area, the PV curve can be plotted against load. Furthermore, RPM can be solved for (equation 3) so that surface velocity can be represented as rotational speed. The result is a handy graphical map of the allowable load and speed for your particular lead screw system. Stay under the curve and the lead screw assembly should be governed by wear failure alone.

Note that there are several ways to manipulate the PV envelope. Changing the polymer compounding or base resin can result in an increase in the limiting PV. This allows the PV curve effectively to be moved up and to the right on the PV chart increasing the system performance (figure 1). Anything that reduces friction between the components will have this effect. This includes compounding lubricants into the plastic, adding grease to the screw or applying a dry film lubricant. In addition, the geometry of the nut can be changed to lower the system PV at a given load and speed. A longer nut will reduce the pressure on the threads for instance. Diminishing returns occur somewhere around a nut length of 4 times the screw diameter.

Given that there is some inherent complexity in calculating the PV of a lead screw system, there is always some uncertainty in the results. However, understanding the relationships and interactions will aid greatly in achieving a functional design. In addition, the manufacturer of the lead screw should provide applications support. This is perhaps the best way to validate PV as they will have the most reliable material and system PV information. In the absence of this information use the following rule of thumb: assume that most catalog load ratings are accurate at a rotational speed of around 500 rpm. Speeds greater than that may require some deration of the operating load. Follow this rule and you'll stay out of trouble!

Questions:

1) What causes a PV failure? In severe cases, friction generated heat builds up until the max use temperature of the nut is exceeded, resulting in a rapid failure. At lower PV's the wear rate is increased, reducing the useful life of the nut.
2) Can I exceed the limiting PV for short periods of time? Yes, if the duty cycle of the application is very low. Unfortunately, once friction generated heat has been created, it takes a considerable amount of time to dissipate. Even 50% duty cycles will just increase the amount of time before the operating temperature of the nut is exceeded. If the application requires that you exceed the limiting PV by a significant amount, duty cycle should be held to 10 or 20%. Remember that if you exceed the load rating of the nut you could cause a structural or mechanism failure, so consult the manufacturer for advice.
3) If I add lubricant to a lead screw how much improvement can I realize in the limiting PV? Actually, most load ratings stated for lead nut products assume a grease or dry film lubricant to achieve the full capacity at 500 rpm. Reduction of friction in a lead screw system has a greater impact on performance than almost anything else. Any opportunity to reduce the friction coefficient should be taken. Consult the manufacturer for any deration that should be applied for operation without lubricant.

Equations

Equation one

$$PV = \frac{\text{Applied force } (\text{lb}_f \text{ or N})}{\text{Projected bearing area } (\text{in.}^2 \text{ or m}^2)} \text{ x Linear Velocity (ft/min or m/s)}$$

Equation two

$$A = l_H \times d_t \times C_f \text{ (in}^2 \text{ or m}^2\text{)}$$

Equation three

$$V = \frac{l_{HR} \times rpm}{60} \ {}^{\text{m}}\!/_{\text{sec}} \ \text{... or}$$

$$V = \frac{l_{HR} \times rpm}{12} \ {}^{\text{ft}}\!/_{\text{min.}}$$

Equation four

$$l_{HR} = \sqrt{(\pi \cdot D_p)^2 + L^2} \text{ (in or m)}$$

Equation five

$$l_H = l_{HR} \times \frac{l_N}{L} \times S_t \text{ (in or m)}$$