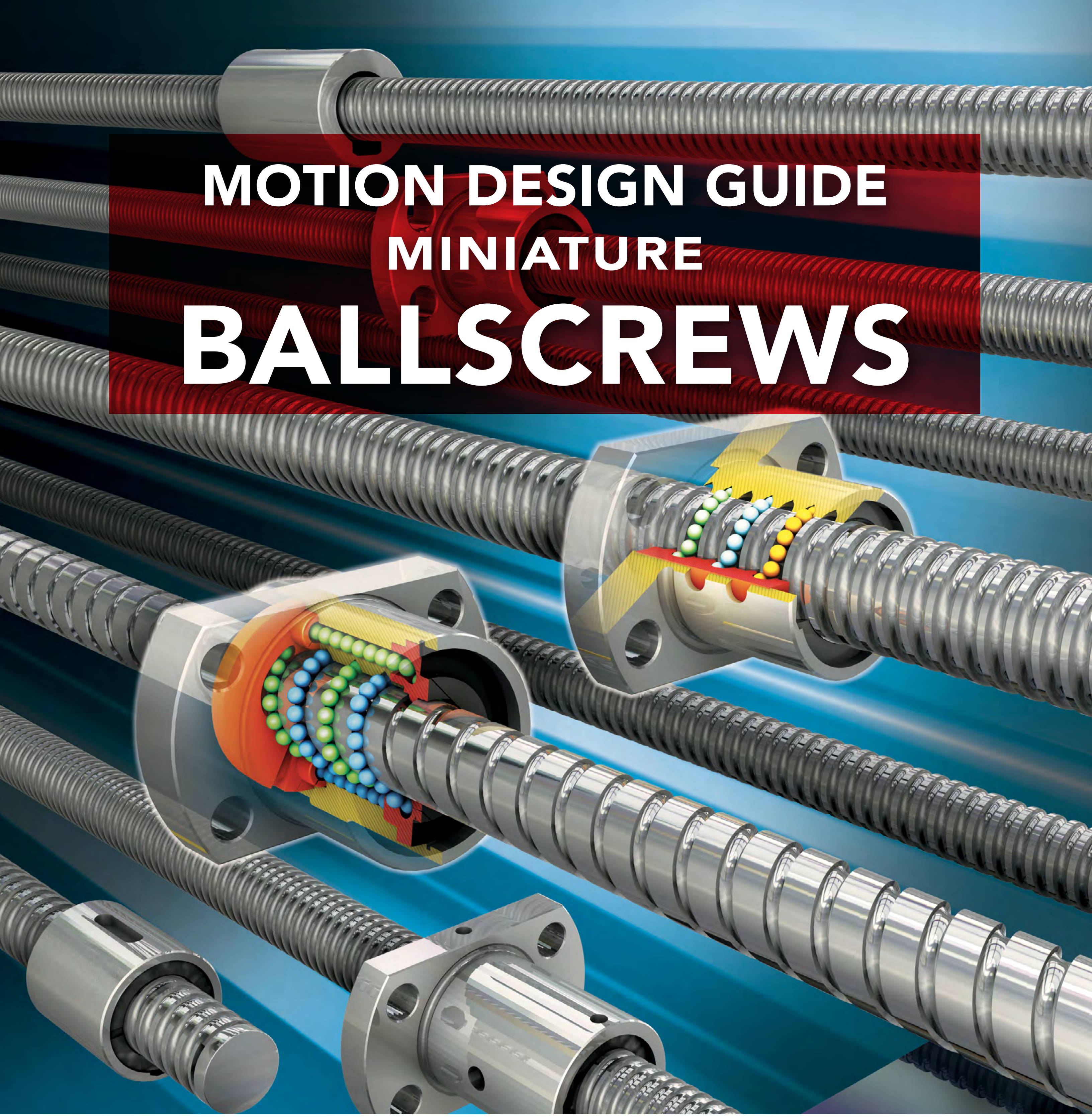
MOTION DESIGN GUIDE
MINIATURE
BALLSCREWS



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BALLSCREWS MOTION DESIGN GUIDE

Core to myriad automated machines and installations are linear motion systems. Most of these pair electric motors with one of three engineered screw types to convert the electric moor's rotary output into linear motion:

Simple leadscrews (sometimes called ACME or trapezoidal, though profiles and flank geometries abound) are based on sliding contact between the linear screw and nut.

Ballscrews are based on rolling contact between the linear screw and nut (via ball bearings).

Roller screws are also based on rolling contact between screw and nut (via rollers).

In this exclusive Design Guide, the editors of Design World present information on ballscrew-based linear-motion drive types.

Of course, determining the most suitable rotary-to-linear screw drive for a given machine axis depends on the loads it will move, travel speeds, duty cycles, cost constraints, and the environment in which the machine will run. That's why in this Design Guide, we'll also review ballscrew load-life characteristics — and why ballscrews excel where high speeds and loads are present … even while maintaining 90% efficiencies.

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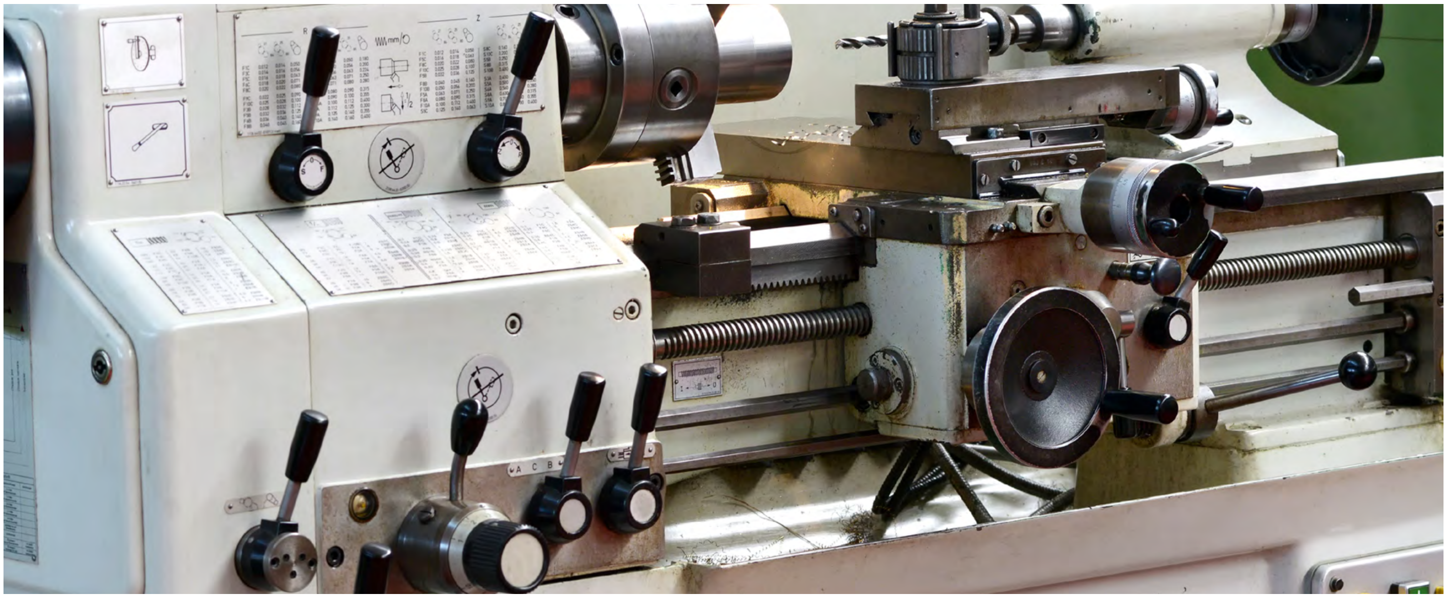
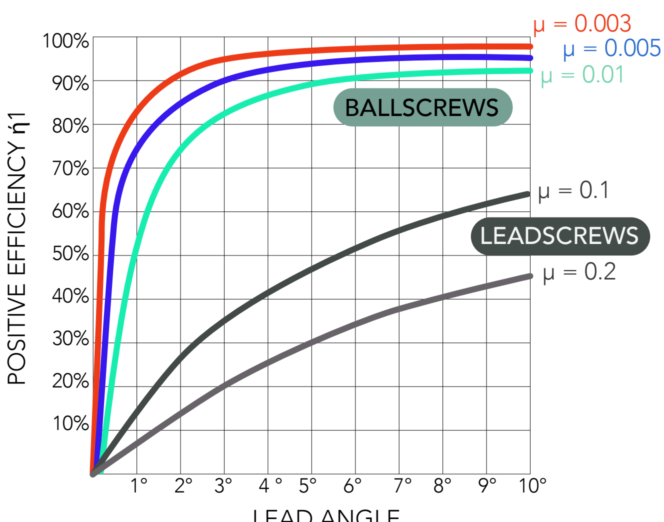


Screw-driven machine-tool (lathe) image © Andreadonetti · Dreamstime

Many of the core linear power-transmission technologies used in today's modern industrial-automation applications have been in use for 50 or more years. However, their design and manufacture (as well as their modes of integration) have continually advanced to allow increasingly sophisticated actuation capabilities and applications. Complementing these modern iterations of mechanical components are motion controls and feedback devices (both electronics hardware and software) with unprecedented functions and flexibility.



Shown here is lead angle versus forward-direction efficiency for various friction coefficients.

Except for pneumatic, solenoid, piezo, electrohydraulic, and linear-motor designs, the core of all linear-motion systems is a rotary electric motor paired with some mechanical rotary-to-linear device. The latter converts the high-rpm rotary motion motor output into a linear stroke. More common options include:

- Ballscrews (covered in this Design Guide)
- Roller screws (planetary and differential types))
- Leadscrews and (especially for vertical applications) jack screws
- Belt drives, chain drives, and pack-and-pinion sets

More exotic power-transmission components for linear motion include:

- Rigid-chain assemblies that lock in one direction to push loads
- Slider crank, disc-cam, and walking-beam drives
- Cylindrical-cam and set axis mechanisms
- Traction drives and skewed-roller rods

Confusing matters is that sometimes these rotary-to-linear mechanical devices are themselves called drives or (worse yet) actuators. In this Design Guide, we reserve the term *actuator* to mean those fully integrated "muscles" that include a motor with or without gearing, coupling if applicable, rotary-to-linear component, and (in most cases) some frame and linear component to bear or support and guide the translated load.

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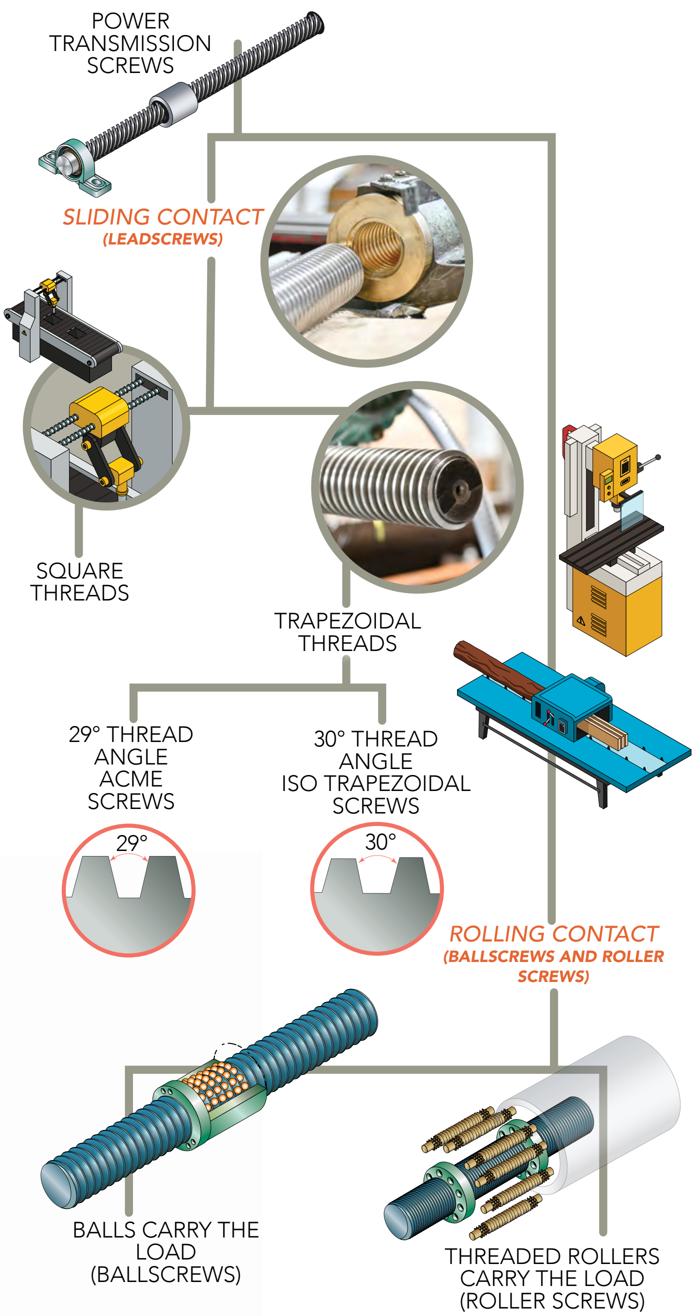
INTRODUCTION TO ROTARY-TO-LINEAR MOTION COMPONENTS

Ballscrews are occasionally called *ball shafts* — especially by global suppliers. A rudimentary form of the component was first proposed in the 1800s with spherical rollers between a leadscrew-type screw and nut pairing. However, not until the 1940s were manufacturing capabilities precise enough to allow the production of ballscrews as they're known today.

These early ballscrew progenitors were widely applied in the U.S. and German automotive industries — as recirculating-ball steering assemblies having nuts threaded on their exterior to make with a worm gear in turn linked to the steering wheel. Further improvements were made to early ballscrew designs by Japanese manufacturers — first for the automotive industry and then for the machine-tool industry. More specifically, computer numerical control (CNC) tools made copious use of ballscrews to replace leadscrews on all three of the machining axes … and ballscrews still find unrivaled use in such machines today.

The load-bearing linear guides most paired with ballscrews and roller screws are track roller linear guides (especially on high-speed axes and those to deliver high thrust force) and profiled rail linear guides. Because screw-driven actuators require end bearings that must be rigidly mounted, they are often enclosed in an aluminum extrusion. However, when high travel accuracy is required, ballscrew types are commonly offered with a machined steel housing.



Electric thrust actuators incorporating both ballscrews and roller screws have come to rival hydraulic cylinders for some applications — capable of delivering hundreds of kN. Shown here is an all-electric GEF-2500 forklift from Greenland Machinery employing such actuation.

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INTRODUCTION TO ROTARY-TO-LINEAR MOTION COMPONENTS

In fact, ballscrew-driven actuators come in both slider and rod types. Slider-type actuators are what most engineers picture when conjuring a linear actuator in their mind's eye. The motion is contained within the limits of a housing and the load is mounted to a slider — also called a carriage, saddle, or table. In rod-type actuators, the motion is produced by a rod that extends and retracts from a housing. The load may be mounted to the end of the rod … or the rod can be used to push the load. One common application is the pressing or stamping of labels onto cartons … or pushing defective products to a diverter lane along a conveyor.

Slider-type actuators can be guided by recirculating or plain bearings, depending on the load for which they're designed. In contrast, rod-style versions are not typically designed for radial loads from downward or sideways force vectors. Instead, they usually include use simple plain bearings to provide guidance to the rod without significantly contributing to load-carrying capacity.

Additional reading:

Options for linear-actuator integration (and motor-screw coupling variations)

Ballscrew and leadscrew drunkenness

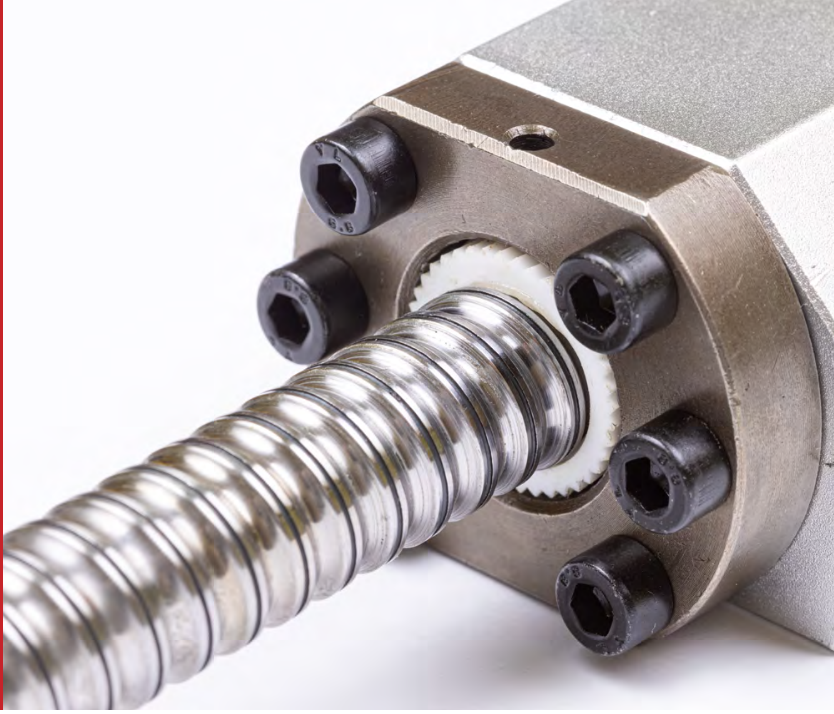
When do axes need a left-handed screw?

Fixed and floating bearings in the context of linear motion

Determining whether a leadscrew or ballscrew will backdrive

Miniature metric ball screws from PBC Linear are precision-rolled with complimenting cylindrical- or flange-style nuts that accommodate long and short leads.
Image Courtesy of PBC Linear

DEFINING LINEAR-MOTION SCREWS WITH THREE KEY ANGLES



Ballscrew nut bolted to a runner block © Photozlaja · Dreamstime

The thread design of a power transmission screw — whether a leadscrew or a ballscrew — plays a critical role in the screw's function. Aside from the basic thread form (Acme, trapezoidal, and so on) the three main aspects of the thread geometry of helix angle, lead angle, and thread angle help to distinguish different types of screws from each other and influence their performance characteristics.

ANGLE 1 OF 3: LINEAR-SCREW LEAD ANGLE

The efficiency of a screw is mainly influenced by three factors: friction, lead, and lead angle. For leadscrews, the high friction produced by sliding contact between the screw and the nut means that friction is the most significant contributor to efficiency. Conversely, because ballscrews use rolling elements with very little friction, their efficiency is primarily dependent on lead angle.

The helical nature of a screw thread can be compared to an inclined plane wrapped around a cylinder — like a rotary wedge. Lead angle is the angle between the helix of the thread and a line perpendicular to the axis of rotation.

Recall from trigonometry that the tangent of an angle equals the side opposite the angle divided by the side adjacent to the angle. So the tangent of the lead angle β equals the lead of the screw divided by the circumference of the screw:

$$tan\beta = \frac{1}{\pi \cdot d_m}$$

$$\beta = arctan\left(\frac{L}{\pi \cdot d_m}\right)$$

Where β = Lead angle
L = Screw lead (mm)
d_m = Root diameter of screw (mm).

Consider sample charts showing the relationship between lead angle and screw efficiency for both ballscrews and lead (sliding) screws. These manufacturer chart show ballscrew efficiency begins to reach its maximum at a 10° lead angle.

For ballscrews, the lead angle also influences the preload torque of the screw assembly used in drive torque calculations:

$$T_p = \frac{0.05}{\sqrt{tan\beta}} \cdot \frac{F_p \cdot L}{2\pi} \times 10^3$$

Where T_p = torque due to preload (Nm); F_p = preload (N); and L = screw lead (mm).

ANGLE 2 OF 3: LINEAR-SCREW HELIX ANGLE

The terms lead angle and helix angle are often used interchangeably, but the helix angle is the angle between the helix of the thread and a line parallel to (rather than perpendicular to) the axis of rotation. Looking again at the depiction of lead and helix angles shows that they are complementary — 90° must be their sum.

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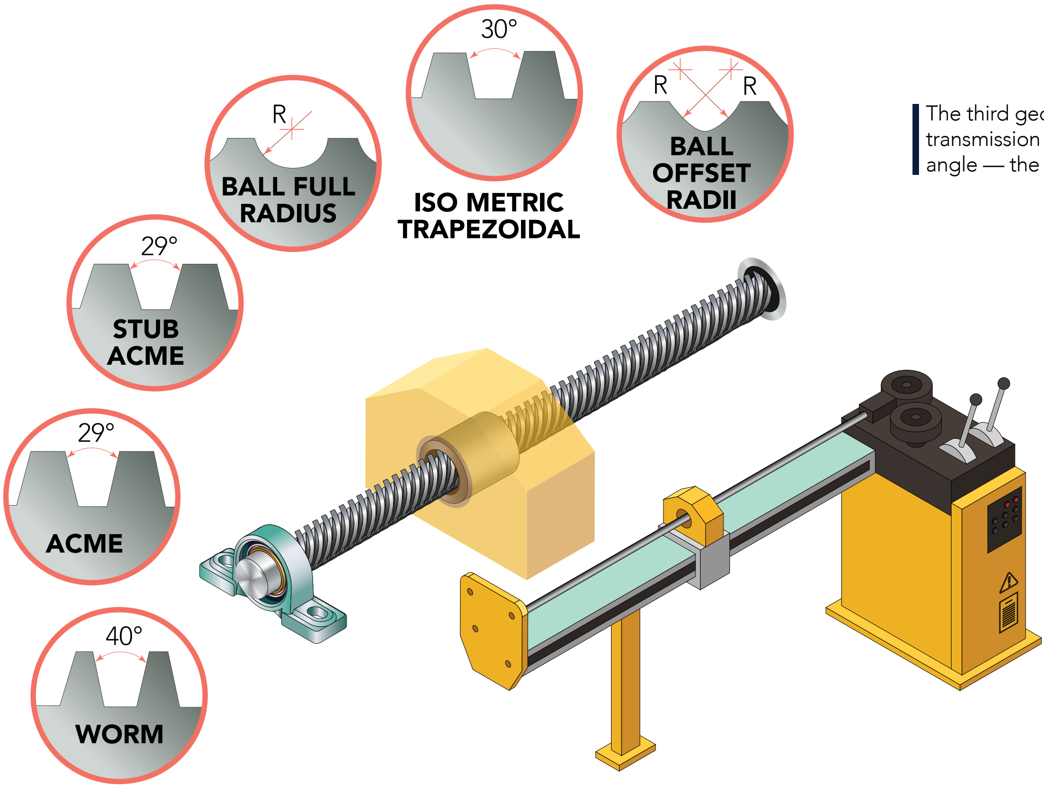
DEFINING LINEAR-MOTION SCREWS WITH THREE KEY ANGLES



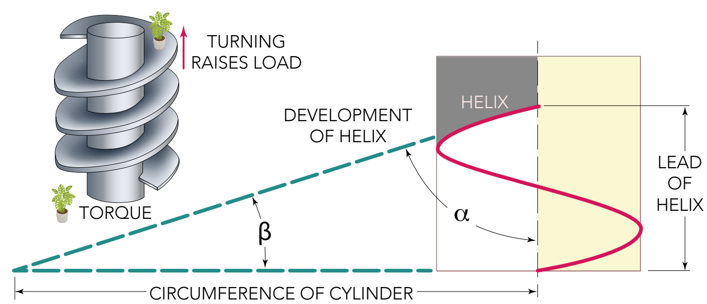
The third geometric specification of power-transmission ballscrews and leadscrews is thread angle — the angle between the shaft threads.

Because the helix angle is the angle opposite the lead angle, its equation is given as:

$$\tan\alpha = \frac{\pi \cdot d_m}{L}$$

$$\alpha = \arctan\left(\frac{\pi \cdot d_m}{L}\right)$$

Helix angle is generally used to describe gear teeth, whereas lead angle is used when referring to screw geometry.



Angle β is the lead angle, and angle α is the helix angle. The smaller the lead ... the smaller the lead angle. In fact, α and β must sum to 90° as they are complementary angles.

ANGLE 3 OF 3: LINEAR-SCREW THREAD ANGLE

Another geometric specification of screws is thread angle, or simply, the angle between threads. Thread angle is a common characterization of leadscrews, with Acme screws having a thread angle of 29° and trapezoidal screws having a 30° thread angle. Ballscrews on the other hand use a radial raceway that conforms to the rolling ball elements, so they are typically characterized by their raceway geometry — Gothic arch or circular arc.

WHEN DO DESIGNS NEED A BALLSCREW?

Ballscrew nut image: Phuchit · Dreamstime

Choosing the wrong product — whether it be an oversized ballscrew or a leadscrew that doesn't provide sufficient life — can lead to unnecessary costs, design rework, frequent replacement, or even failure. Here we review common requirements that call for the use of ballscrews over leadscrews.

Complicating matters is how the gap is narrowing between applications that require ballscrews and those that are suitable for leadscrews. That in turn has made it increasingly difficult for engineers and designers to determine which technology is best for a given machine. Advances in leadscrew designs and materials have given them higher load capacities and better positioning accuracy, making them a sound choice for more than just the low-cost and low-precision applications in which they were used in the past.

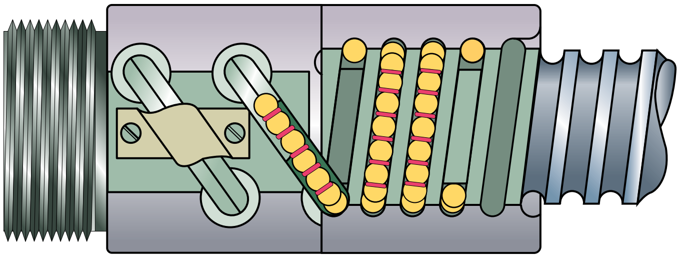
As already covered in this Design Guide, leadscrews incorporate a screw and a plain nut (with no rolling mechanisms). They rely on the angle of the thread and friction between the nut and the screw to produce motion. The screw is typically made of either carbon steel or stainless steel, while the nut can be bronze, plastic, or polymer.

Ballscrews also incorporate a screw and a nut — but differ in that the nut houses recirculating balls to carry the load. This design minimizes friction and provides high efficiency.

Despite the growing overlap in their technical capabilities, however, there are still best-fit applications for each technology. In some cases, the application requirements simply exceed the capabilities of a leadscrew, and only a ballscrew will perform as needed. Below are four common application criteria that (in most cases) require a ballscrew.

BALLSCREWS TRANSPORT HEAVY LOADS

With recirculating steel balls to support the load, ballscrews have a higher load capacity than comparably sized leadscrews with plastic or polymer nuts. Leadscrews with bronze nuts can drive heavier loads, but as the load increases, so does friction.



Many ballscrew advantages over leadscrews are due to the recirculating balls that support the load.

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WHEN DO DESIGNS NEED A BALLSCREW?

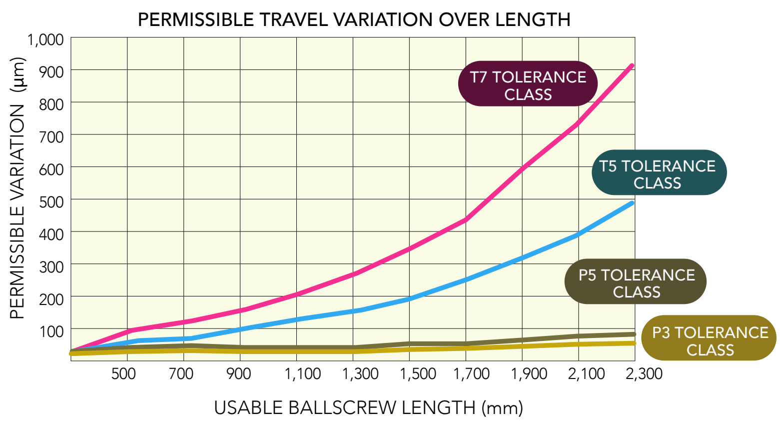
Higher friction in turn makes for a lower possible duty cycle (covered in more detail later in this Design Guide).

Also related to load, ballscrew sizing is based on the L10 bearing life equation, which provides a statistically proven estimation of the screw's life, in meters or rotations traveled. The wear characteristics of a leadscrew make life nearly impossible to predict. Leadscrews with plastic nuts can be selected based on their PV value, but this gives a range of pressures and velocities that the screw can withstand — not an estimation of life.

SATISFYING HIGH ACCURACY REQUIREMENTS

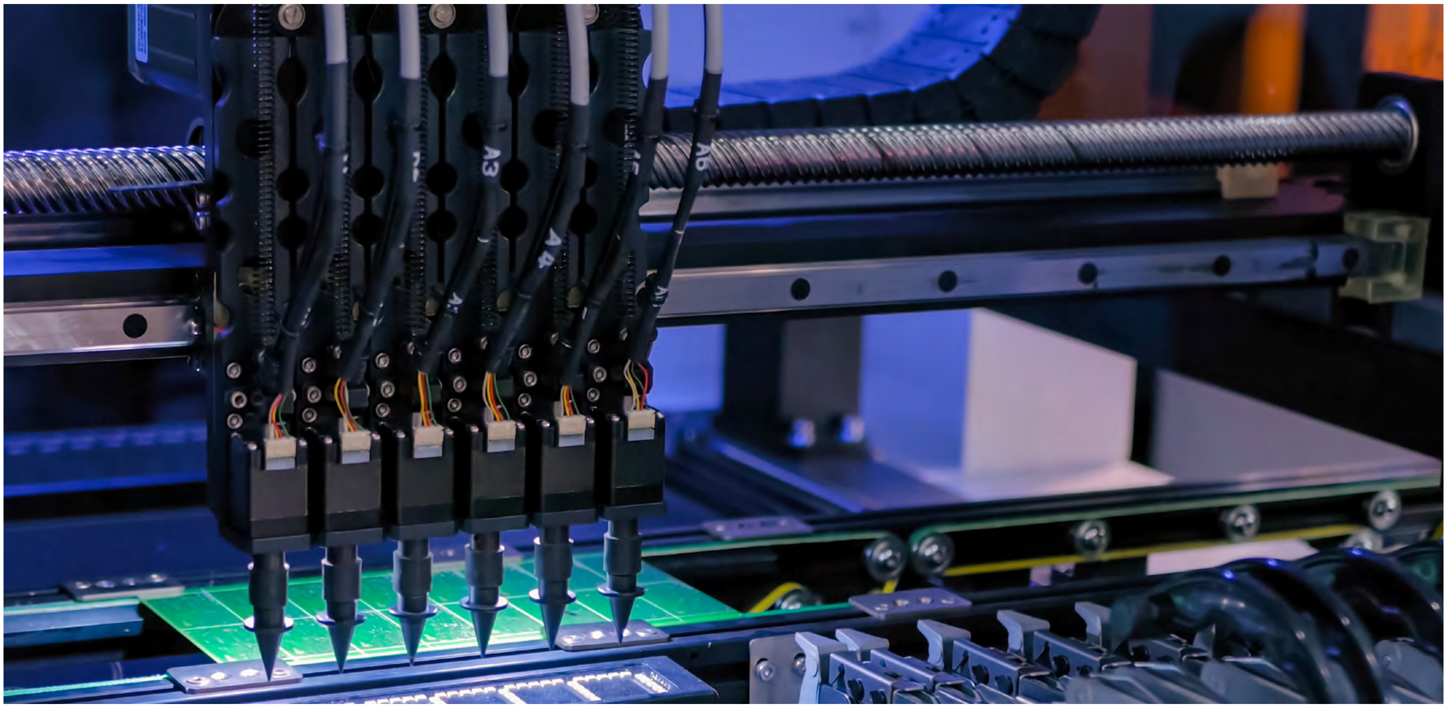
Unlike leadscrews, which have backlash between the nut and the screw, ballscrews can be, and often are, preloaded to remove backlash. This is typically done by using balls that have a slightly larger diameter than the space between the raceways of the screw and the nut. (Some leadscrews are offered with nut designs that eliminate backlash, but these typically add friction and reduce efficiency.)

In addition, ballscrews are classified by ISO, DIN and JIS standards regarding their lead deviation, so choosing the proper accuracy class ballscrew is straightforward.



International standards (ISO, DIN, and JIS) define the allowable travel deviation for each ballscrew accuracy class.

This is a ballscrew application in an automatic SMT pick-and-place machine. Image: Andrii Chagovets · Dreamstime



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WHEN DO DESIGNS NEED A BALLSCREW?

Screws can both drive and guide vertical linear motion on robotic end-effector axes. Some variations are rotary+stroke units sporting both ballscrew and ball-spline grooves that cross on the shaft surface.

HIGH EFFICIENCY THANKS TO ROLLING CONTACT

Rolling elements such as the balls in a ballscrew assembly rely on point contact to support a load. In contrast, sliding elements such as the screw and nut of a leadscrew assembly rely on line contact. Point contact produces less friction, which gives the assembly higher efficiency. Case in point: ballscrew efficiency is almost always 90% or better, while leadscrew efficiency is normally below 50%.

High efficiency translates to lower required motor torque … which means that a smaller motor (and related components) may be suitable for the application.

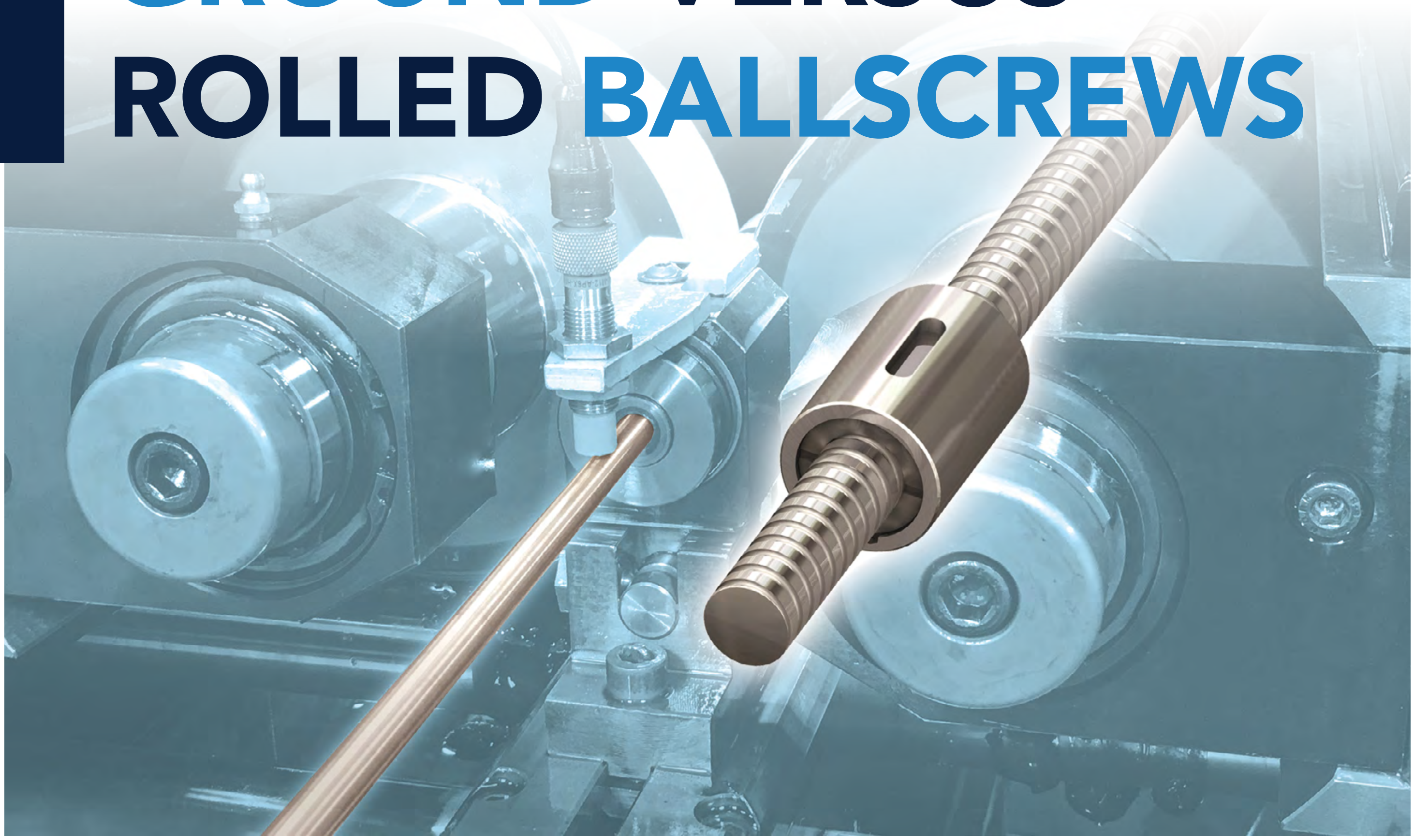
BALLSCREWS WITHSTAND DEMANDING DUTY CYCLES

The maximum speed of both leadscrews and ballscrews is limited by the critical speed of the screw. However, the lower friction inherent in ballscrew designs means they produce less heat and therefore can withstand higher duty cycles than leadscrews can. In fact, duty cycle is only considered in ballscrew selection when determining the amount of travel that the screw will achieve in its calculated life. On the other hand, duty cycle and heat generation must always be considered when selecting a leadscrew.

Like plain linear guides with sliding friction, leadscrews with plastic nuts must adhere to their maximum pressure x velocity (PV) value.

PBC Linear offers both high-precision miniature ball screws and lead screws that fit many small-scale applications.
Image Courtesy of PBC Linear

GROUND VERSUS ROLLED BALLSCREWS



Small diameter screws from PBC Linear use a precision-rolled CNC process to achieve lead accuracy and consistency over the full length of the screw. Image Courtesy of PBC Linear

There's much debate among manufacturers and sometimes among users regarding the superiority (or lack thereof) of ballscrews with ground threads over those with threads that are formed by rolling. Ground ballscrews have traditionally been the choice for high-precision applications, whereas rolled screws offered an economical solution for general industrial and automation applications. But manufacturing technologies have changed over the last several decades and rolled ballscrews are no longer the pepper grinder devices that some users experienced in the past.

Here are three facts to keep in mind when determining which to use in any machine or process.

❶ DIN/ISO AND JIS SPECIFICATIONS DISTINGUISH BETWEEN BALLSCREW ACCURACY PRECISION (P) AND BALLSCREW ACCURACY TRANSPORT (T).

The lower the number, the better the accuracy, with precision classes ranging from P0 to P5 and transport classes from T5 to T9 (T10 for JIS). JIS specifications denote accuracy classes with the prefix C for precision and Ct for transport.

A common misconception is that the accuracy class specifies the manufacturing method, but the two are not intertwined. Rolled screws can be made in ***P5*** and even ***P3*** accuracy, and some ground screws only meet T accuracy requirements. The important thing to understand is whether, according to the manufacturer's specifications, the lead error v300 accumulates over the length of the screw. ***P*** accuracy classes do not allow lead error accumulation while ***T*** accuracy classes do.

(continued)

GROUND VERSUS ROLLED BALLSCREWS

Rolled ballscrews (left) are less precise than ground (right).

❷ GEOMETRIC TOLERANCES ARE ALSO SPECIFIED BY DIN/ISO AND JIS STANDARDS.

For ground ballscrews, both thread grinding and journal grinding are done using the same reference centers, making it easier to minimize radial run-out and to keep the screw threads and end journals concentric.

When screws are manufactured by rolling, the end journals are machined and ground after the threads are rolled, so maintaining concentricity and run-out is more difficult. However, if a ballscrew is manufactured to DIN/ISO or JIS standards, it will meet lead accuracy specifications and also the geometric specifications — *regardless of whether it was manufactured by rolling or by grinding*.

❸ THE ROLLING AND GRINDING PROCESSES PRODUCE DIFFERENT SURFACE FINISHES.

A rough surface finish is problematic in ballscrew assemblies because it can result in higher friction and more wear on the load-carrying balls.

The grinding process produces a smooth surface finish — and (in theory) the rolling process does as well. But in reality, rolled screws must also be polished to remove an oxidation layer that forms during the rolling process. So when considering surface finish, the comparison is not between the ground surface and the rolled surface. The comparison is *actually* between the ground surface and the polished surface of rolled screw. The quality of the polishing step and not the rolling process determines the surface finish quality of a rolled screw.

As with most design criteria, the decision regarding the most suitable ballscrew type depends on performance requirements and cost. Ground screws are necessary when ballscrew accuracy below P5 is required, as the rolling process cannot produce these accuracy classes. But for P5 and in some cases P3 accuracy, both rolled and ground screws can satisfy required specifications. For accuracy classes 7 and 9 (10 by JIS standards) either manufacturing method can produce ballscrews that meet DIN/ISO or JIS standards.

Final note on ballscrew preload: Applications that use linear bearings or ballscrews often require precise positioning, which means that the motion components must be rigid. While recirculating ball guides and screws can carry large loads, they inherently have clearance, or backlash, due to the size and fit of the balls between the raceways. To eliminate this backlash and increase rigidity, preload must be applied.

PRELOAD IN SCREW DRIVES

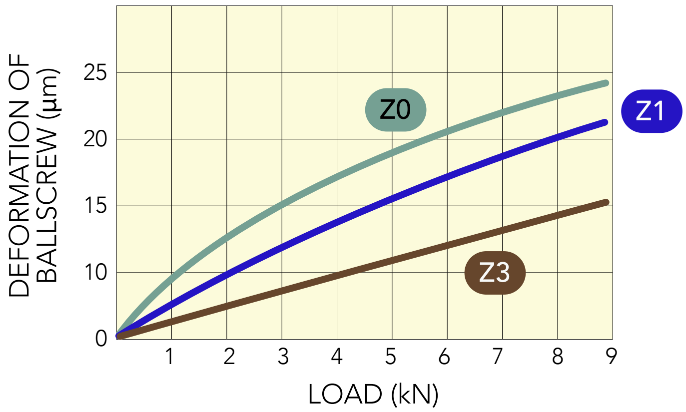
AND THE LINEAR GUIDES THAT COMPLEMENT THEM

Preload is the elimination of internal clearance between the rail and carriage (for linear bearings) or between the screw shaft and ball nut (for ballscrews). This makes the system more rigid by creating a load on the linear guide (or ballscrew) to reduce deflection when an external force is applied. It can also take-up play and reduce issues associated with vibration.

For track-roller linear guides, preload is typically achieved by adjusting eccentric adjustable cams on the guide block. These cams draw steel wheels on one of the two sides of the guide block into the linear rail for an overall tighter assembly.

For profile-rail linear guides, preload is achieved by loading the guide block with balls having diameters slightly larger than the distance between the block and rail raceways — in other words, by including oversized balls.

The diameter of the balls relative to the distance between raceways determines the amount of preload that is reached.



These are the deflections of linear guides with no preload (Z0), light preload (Z1), and medium preload (Z3).

Common preload amounts for linear guides are 2, 5, or 8% of the dynamic load capacity. For example, a linear guide with a dynamic load capacity of 25,000 N and 2% preload has a preload force of 500 N.

Some manufacturers supply preloaded linear-bearing systems as matched rail and carriage sets. With these products, if the carriage is used on a guide rail different than its original mate, specified preload cannot be guaranteed. No wonder it's increasingly common that manufacturers provide interchangeable carriages and rails — for ease of servicing, specifying, and inventory. For such offerings, preload is specified and set in the carriage — so the carriages work on different rails while maintaining the same preload. When specifying a preloaded linear guide, it's important to be aware of which type (matched set or interchangeable) the chosen manufacturer provides.

PRELOAD FOR BALLSCREW ASSEMBLIES

There are multiple ways to achieve preload for a ballscrew system, with the most common three being the use of:

- Oversized balls in the ball nut
- An adjustable-diameter ball nut
- A double-nut system.

The first approach (using oversized balls) is analogous to the method used to preload profiled-rail linear guides. These balls are loaded into the ball nut to eliminate the clearance between the screw and nut raceways. This is a relatively low-cost option and can be achieved with a variety of nut styles, making it a common choice for applications requiring low preload.

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PRELOAD IN SCREW DRIVES

BALLSCREW PRELOAD	USEFUL FOR ...	TYPICAL USES
Clearance (no preload)	Minimum-friction force • Vertical axes	Material handling and packaging machinery
Light preload — 1% to 3%	Addressing moment loads or ensuring positioning accuracy	Test and inspection equipment • Semiconductor manufacture
Medium preload — 4% to 6%	High stiffness	Medical imaging • laser-cutting equipment
Heavy preload — 7% to 10%	Addressing vibrations and impact loading	Boring machines and various machine tools

For applications in which preload doesn't need to be set to a precise amount (*or when it should be variable to correct for changing application conditions or wear*) an adjustable nut is the most suitable option. In this case, the nut has a C-shaped slot containing an adjusting screw. Tightening the latter decreases the nut's internal diameter to eliminate clearance between the nut and screw-shaft raceways — and increase preload. The adjustable nut method is inexpensive and allows flexibility, but preload cannot be set to an exact amount. Therefore, it's most found on ballscrew applications for which rigidity is important but noncritical.

When high preload amounts (typically between 7 and 10%) are required in a ballscrew system, the most suitable preload method is to tension two single nuts against each other using a spacer or spring between them. This method is also called a double-nut system — and is found in applications where rigidity is critical and vibrations or shock loads are present … such as machine tools, for example.

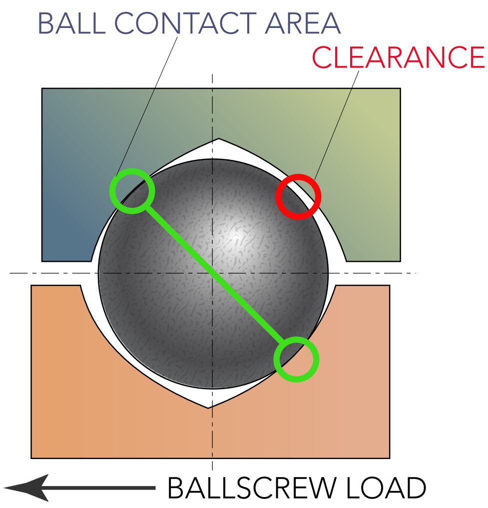
Double-nut designs produce preload either through tension between two single nuts or through an offset in one nut's lead. The first method uses a spring or a spacer to create tension between two mechanically coupled nuts. The second double-nut preload method features a lead offset permanently machined into the ball-nut raceway during manufacture about halfway down the nut's length.

Because there are no spacers or springs required with this second approach, it's more compact than a double nut design … but reduces load capacity.

Double-nut systems provide the most rigidity but are the most technically challenging to install. They also require nearly twice the length of a single nut, so taking up valuable travel length in space-constrained applications.

HOW TO CHOOSE THE CORRECT PRELOAD

When it comes to choosing preload, more is not necessarily better. Preload increases the force (or torque) required to move the linear carriage (in the case of a linear guide) or ball nut (in the case of a ballscrew). That in turn can require a larger motor and related components with higher cost and complexity. High preload also causes additional heat to be generated inside the carriage (or ball nut) which increases wear and reduces life. Finally, preload is in fact a load applied to the linear bearings of a system — so linear-bearing life calculations must account for its effect (in all cases, amplified by the cubed power in linear-bearing life equations).



Ballscrew assemblies can be preloaded with oversized balls that prevent clearance between screw shaft and nut raceways. This eliminates axial play (backlash).

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PRELOAD IN SCREW DRIVES (AND THE LINEAR GUIDES THAT COMPLEMENT THEM)

MORE ON BALLSCREW PRELOAD BENEFITS

We've now outlined how ballscrew preloading can ensure high thrust force and rigidity along with good positioning accuracy … and how the three main modes of adding preload are with oversized balls in the ball nut (most common), an adjustable-diameter ball nut, or a double nut system (second most common). Creating preload by using oversized balls allows the manufacturer to set the preload to a precise amount for preload amounts less than 5% or so.

In contrast, adjustable-diameter ball nuts let technicians manually adjust preload via an adjustment screw … a convenient feature for applications that may see a change in required preload over time. Although they don't facilitate setting the preload to very precise level, another benefit of systems employing adjustable nuts is that they accept replacement ball nuts (manually preloaded) if needed.

BALLSCREW PRELOAD REDUCES AXIAL PLAY AND INCREASES RIGIDITY

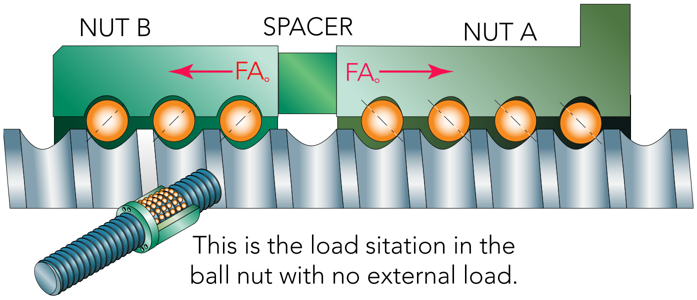
In many applications, the primary reason for using a preloaded ballscrew is to reduce internal clearance between the raceways of the nut and screw — a cause of backlash. Though preload doesn't affect lead error or positioning accuracy, the way it reduces backlash boosts axis repeatability, because there is no lost motion upon travel reversal.

$$\frac{1}{R_{tot}} = \frac{1}{R_s} + \frac{1}{R_N} + \frac{1}{R_B} + \frac{1}{R_H}$$

In fact, high preload also correlates with high nut rigidity, which boosts overall ballscrew-system rigidity. But because the ball nut is only one component in the ballscrew assembly, and its rigidity is relatively high compared to the other components, increasing the preload — from 3% to 5%, for example — has a minimal effect on assembly rigidity.

The most noticeable increase in rigidity of a ballscrew assembly occurs when a non-preloaded ball nut is replaced with a preloaded version.

One way to produce preload in a ballscrew assembly is to use a double ball nut, with either a spacer or spring between the two nuts.



PRELOAD ALSO INCREASES MOTOR DRIVE TORQUE AND DECREASES LIFE

Another effect of ballscrew preload is that it induces an internal load on the ball nut, which needs to be considered during sizing to ensure the motor can produce sufficient torque for the application. Preload is specified as a percentage of the ball nut's dynamic load capacity. So to determine the internal load due to preload, the preload amount (0.02 for 2% or 0.07 for 7% for example) is multiplied by the dynamic load capacity.

The applied load ***F*** component of the bearing life equation must account for the load due to preload. Because of the cubic nature of the equation, even a small internal load due to preload can significantly degrade ballscrew life:

$$L = \left(\frac{C}{F}\right)^3 x\,100{,}000$$

Note that when the external load meets or exceeds 2.8 times the internal load due to preload, it counteracts the internal load, and the internal load can be disregarded.

Additional reading:

The relationship between ballscrew preload and axial deflection

Still more on ballscrew preloading

Ballscrew nut-based loading and system life

HOW TO AVOID **BALLSCREW BUCKLING**

One potential concern with ballscrews is buckling. To understand why, imagine two columns — one short and wide … and the other long and narrow. As weight is applied to these two columns, the long and narrow one gradually begins to bend until it becomes permanently deformed and eventually breaks. In contrast, the short and wide column handles the weight with ease.

In the same way a thin column reaches its buckling point earlier than a squatter column — so too does a long ballscrew with a small diameter deform and buckle under a smaller axial load than a shorter screw with a larger diameter.

Determining the buckling load is key to ballscrew sizing. The buckling (compressive) load can easily be calculated based on the screw's root diameter, unsupported length, and end bearing configuration:

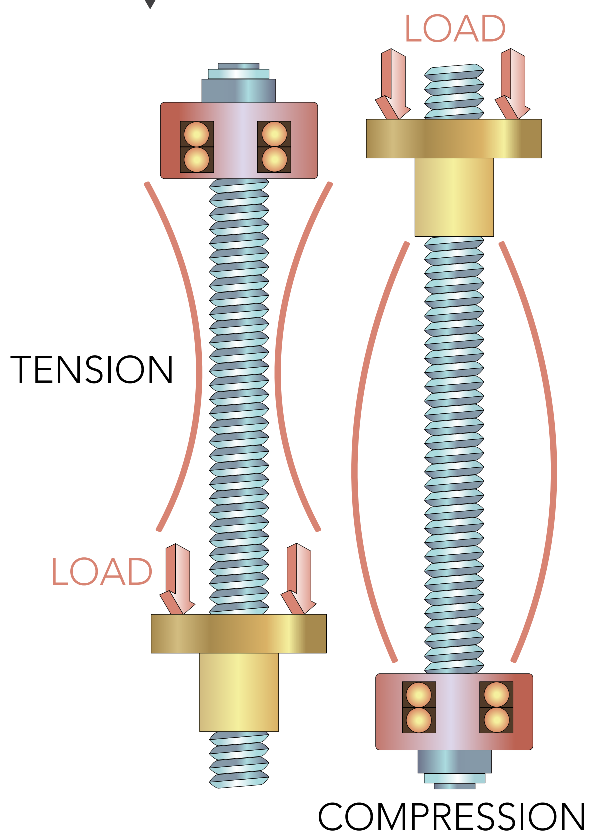
$$F_c = f_b \cdot \left(\frac{d_1^4}{L^2}\right) \cdot 10^4$$

Where F_c = maximum compressive load (N)
f_b = End bearing factor
d_1 = Root diameter of screw (mm)
L = Unsupported length (mm).

Application tip: The end bearing factor f_b is dependent on the end fixity of the screw. Ballscrew manufacturers recommend a safety factor of at least 2 for the maximum applied buckling load, and some incorporate this into this published end bearing factors.

To avoid over or undersizing, check whether the manufacturer has built a safety factor into the published fb values.

Buckling is a relatively straightforward but sometimes overlooked factor in ballscrew sizing. Always check process forces in horizontal applications and the location of the fixed bearing in vertical applications. For the latter, orienting the fixed bearing on top puts the ballscrew in tension.



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HOW TO AVOID BALLSCREW BUCKLING

For a given diameter and length ballscrew, permissible buckling load can be increased by changing the support bearing arrangement.

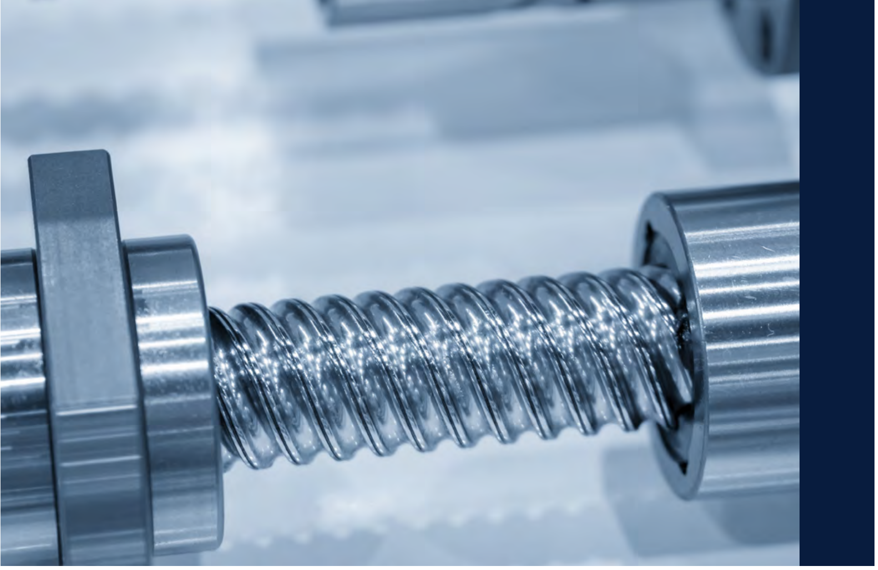
The more rigid the support bearings, the higher the bearing factor … ranging from approximately 2.5 for a fixed-free arrangement to 40 for a fixed-fixed arrangement. This means that a fixed-fixed bearing arrangement will result in approximately sixteen-fold the permissible buckling load than a fixed-free arrangement on the same screw assembly.

In a horizontal application, axial force is generally equal to the load times the screw assembly's coefficient of friction … so buckling is typically less problematic than other performance factors such as critical speed or drive torque. But some horizontal applications (such as pressing and injecting) introduce an additional axial load on the screw assembly — and the buckling load can easily become a constraining factor in screw selection.

When a ballscrew is used in a vertical application, it sees the full load as an axial force. That force renders buckling a more acute concern. Mounting a screw assembly with the most rigid support (typically a fixed bearing) at the top puts the screw in tension rather than compression and counters the effects of the axial load. In the unusual case of a high reversing force — for example, pushing a plunger into a housing on the screw's upward stroke — the most beneficial bearing arrangement is to orient the fixed bearing at the bottom of the screw assembly.

Another application tip: Most but not all screw-driven linear actuators use a fixed bearing on the motor side and a floating bearing on the non-driven end. For vertical applications, be sure to check which end of the actuator includes a fixed bearing to avoid excess compressive forces on the screw.

The assemblage of precision-rolled screw, ball return nut and end blocks, and NEMA 23 motor combine to create a high-performance linear motion actuated system from PBC Linear. Image Courtesy of PBC Linear



Ballscrew in a CNC machine: Phuchit · Dreamstime

HOW TO CALCULATE BALLSCREW RIGIDITY

The rigidity of a ballscrew determines the amount of elastic deformation it will experience in the axial direction, under a given load. Elastic deformation and therefore rigidity is a fundamental characteristic in selecting and sizing a ballscrew, as it affects system positioning accuracy:

$$\delta = \frac{F_a}{R_{tot}}$$

Where δ = Elastic deformation (μm)

F_a = Applied force in axial direction (N)

R_{tot} = Rigidity of the screw assembly (N/μm)

In this equation, the value for rigidity is based on the screw assembly, not simply the screw shaft or the ball nut. A complete screw assembly typically includes the screw shaft, ball nut, support bearings, and housings for the ball nut and bearings … all of which contribute to rigidity:

$$\frac{1}{R_{tot}} = \frac{1}{R_s} + \frac{1}{R_N} + \frac{1}{R_B} + \frac{1}{R_H}$$

Where R_{tot} = Rigidity of the screw system (N/μm)

R_S = Rigidity of the screw shaft (N/μm)

R_N = Rigidity of the ball nut (N/μm)

R_B = Rigidity of the support bearings (N/μm)

R_H = Rigidity of the ball nut and bearing housings (N/μm)

Rigidity of the ball nut and support bearings are given by their respective manufacturers, while rigidity of the housings depends on their construction and mounting. But besides these components, screw-shaft rigidity tends to be the lowest of all the components … and based on the inverse nature of the equation, has the biggest influence on total system rigidity.

Screw shaft rigidity depends on the end bearing arrangement, the minor diameter of the screw, and the distance between the thrust bearing and the ball nut. For a fixed-free or fixed-floating arrangement, the screw shaft rigidity is:

$$R_S = \frac{A \cdot E}{1000 \cdot L}$$

$$A = \frac{\pi}{4} d_1^2$$

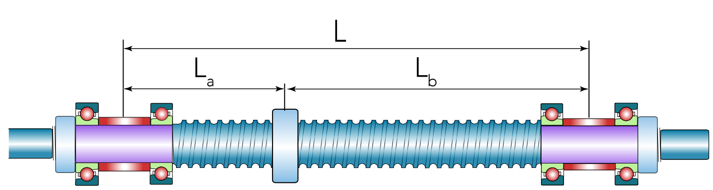
Where A = Cross-sectional area of the screw (mm^2)

d_1 = Minor diameter of the screw (mm)

E = Modulus of elasticity of steel (2.06 x 105 N/mm)

L = Distance between the ball nut and the fixed bearing (mm)

When the end-bearing arrangement includes two fixed ends, the rigidity of the ballscrew shaft is influenced by the distance of the ball nut from each of the fixed end bearings:



Fixed-fixed arrangements have the shortest unsupported lengths.

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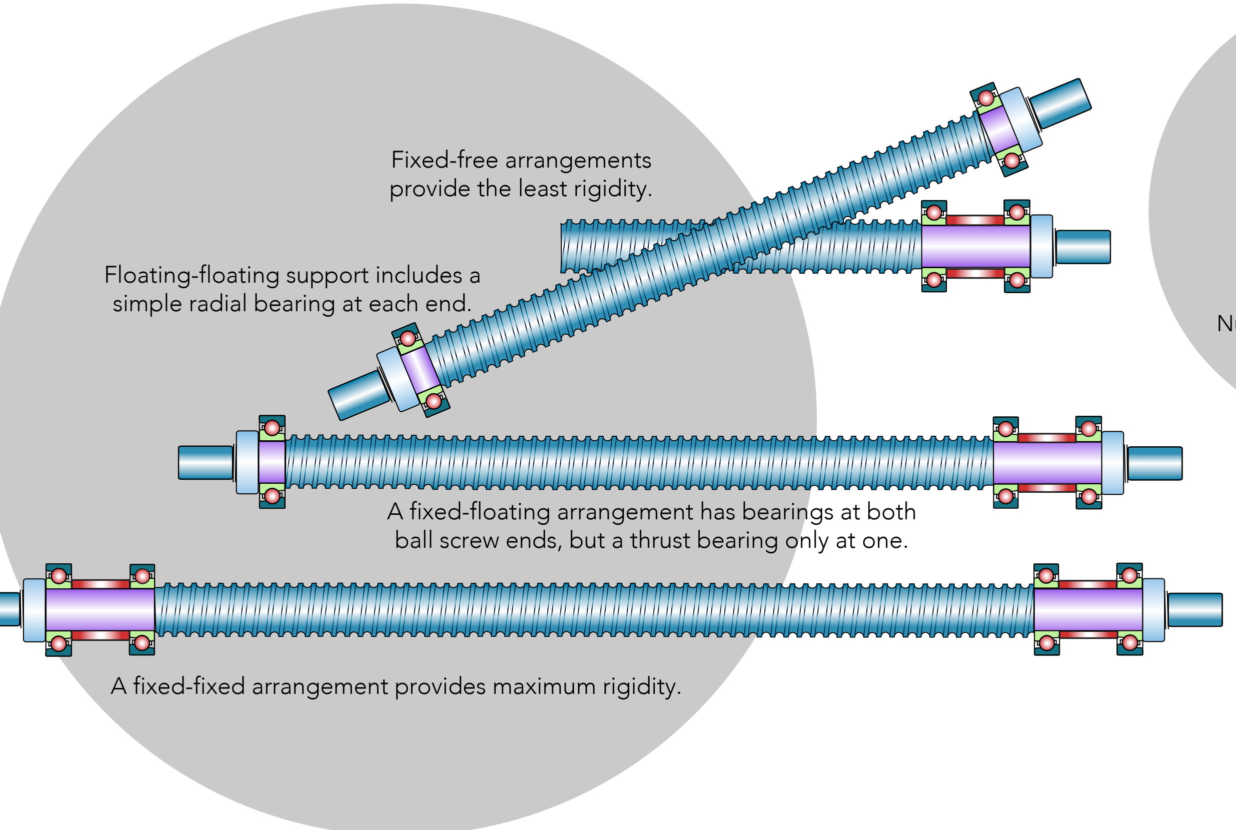
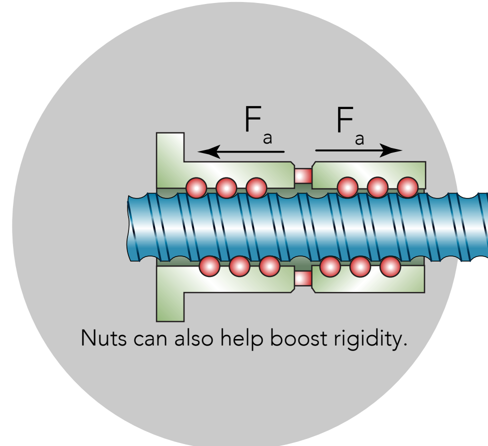
HOW TO CALCULATE BALLSCREW RIGIDITY





$$R_s = \frac{A \cdot E \cdot L}{1000 \cdot L_a \cdot L_b}$$

Where L_a = Distance between the ball nut and one fixed bearing (mm)

L_b = Distance between the ball nut and the other fixed bearing (mm)

In the fixed-fixed arrangement, the rigidity will be lowest when the ball nut is located halfway between the two fixed ends with $L_a = L_b = L/2$ — and the rigidity equation then becomes:

$$R_s = \frac{4 \cdot A \cdot E}{1000 \cdot L}$$

The equations show that rigidity for ballscrew assemblies having fixed-fixed mounting is quadruple that for assemblies with fixed-free (or fixed-floating) mounting. That means the end-bearing configuration is the first thing to consider if a screw assembly is not rigid enough for the application.

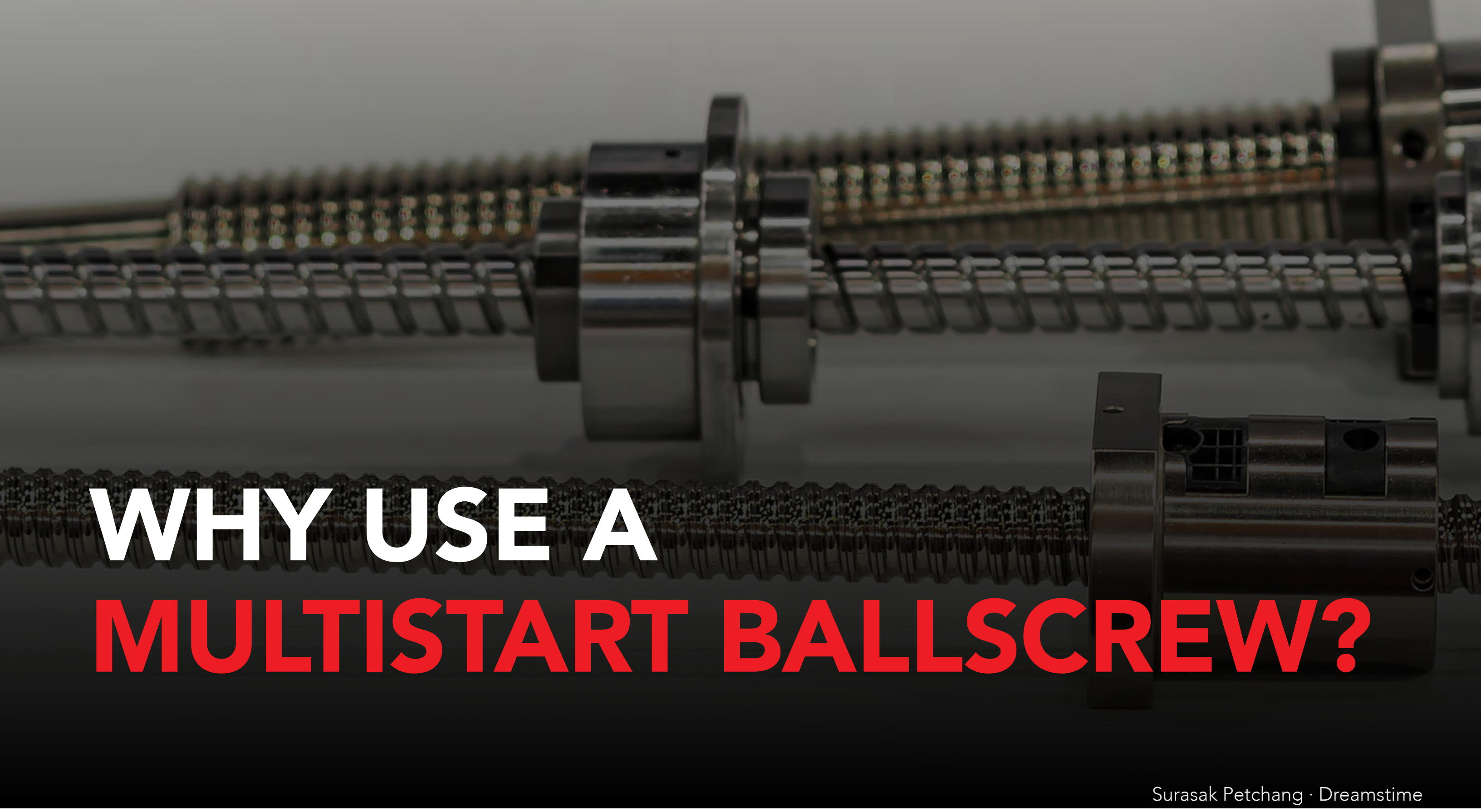
Another method to improve rigidity is to use a larger diameter screw. This increases not only the rigidity of the screw shaft, but also of the ball nut and (in most cases) of the end bearings.

Conversely, increasing the preload of the ball nut generally has only a small effect on rigidity, because the ball nut is a minor factor in the total system rigidity. Increasing preload also has the potentially detrimental effect of higher frictional torque, more heat generation, and greater material expansion of the screw shaft.

Additional reading:

How to improve ballscrew rigidity

Benefits of a rotating nut (driven nut)



WHY USE A MULTISTART BALLSCREW?

Surasak Petchang · Dreamstime

The easiest way to get higher speed from a ballscrew assembly (within the screw's critical speed limit, which is based on diameter, length, and end fixity) is to use a higher screw lead. But increasing the lead of the screw has a drawback: As the lead increases, the number of effective turns in the ball nut is reduced. This means fewer balls in the load-carrying zone, and as a result, lower load capacity.

But a high-lead ballscrew has a great deal of deadspace between the ball tracks — space that can be used for additional independent ball tracks. More ball tracks mean more effective turns, more load-carrying balls, and higher load capacity.

A ballscrew with multiple, independent ball tracks is called a multistart ballscrew.

Multistart ballscrews and nuts have several advantages, with the first being the increase in load capacity compared to single-start versions. They also offer a safety mechanism not found in single-start screws. If one start, or ball track, is damaged, balls in the other track(s) can still help to carry the load and prevent immediate, catastrophic failure. Plus using a single-start ball nut on a multistart screw shaft can reduce maintenance costs. If the ball nut becomes damaged, it can be removed, and a new nut can be installed on a different unused track of the ballscrew shaft. This can provide a significant time and cost savings by avoiding the need to disassemble and replace the entire screw and nut assembly.

When using a multistart ballscrew, there are some design and operation considerations that differ from single-start screws. One of these considerations is end bearings. The standard end bearings for a given size (diameter and lead) single-start screw may not have enough capacity to support the higher load capability of a multistart screw of the same size — necessitating the use of larger or heavier-duty end bearings.

Another consideration is sealing. Multistart ballscrews have different cross-sectional profiles than single-start screws. So if ball nut seals are ordered separately from the screw assembly or (if they need to be replaced in the field) ensure they're designed for the appropriate number of starts on the ballscrew.

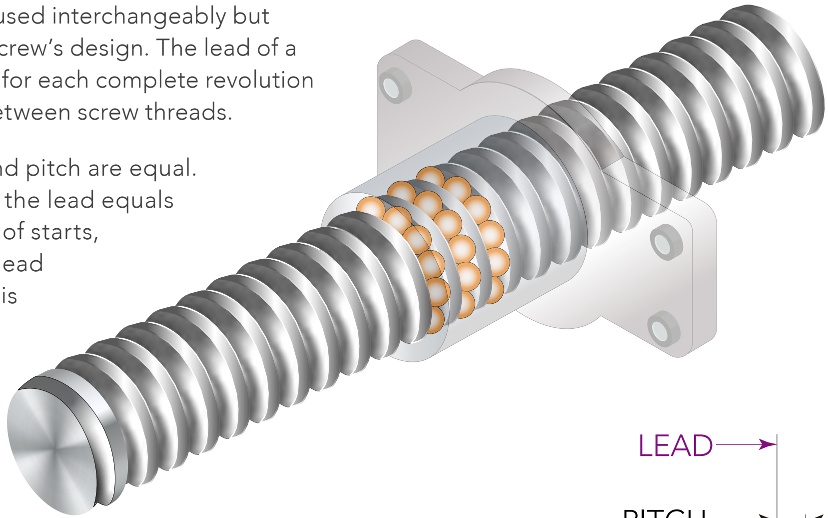
In terms of operation and maintenance, multistart ball nuts typically require a larger quantity of lubrication than single-start versions, due to the larger number of balls in the load-carrying zone. This makes it important to check and follow the manufacturer's lubrication recommendations for the specific, multistart ball nut being used.

(continued)

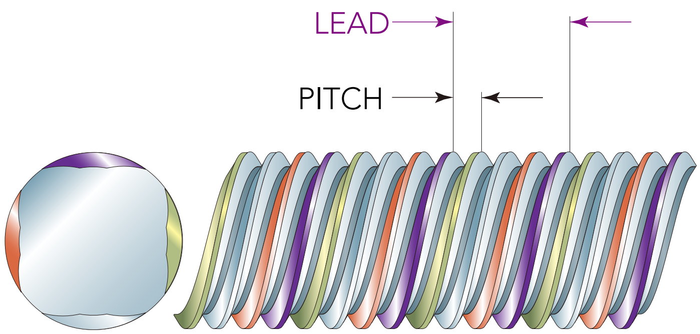
WHY USE A MULTISTART BALLSCREW?

The terms ***lead*** and ***pitch*** are often used interchangeably but they refer to different aspects of a screw's design. The lead of a screw is the linear distance traveled for each complete revolution of the screw. Pitch is the distance between screw threads.

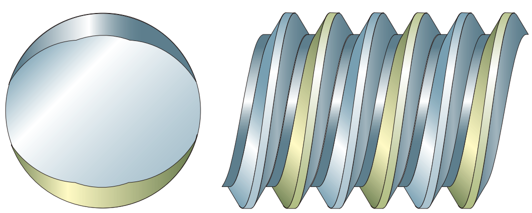
For a single-start screw, the lead and pitch are equal. However, for a multistart ballscrew, the lead equals the pitch multiplied by the number of starts, or conversely, the pitch equals the lead divided by the number of starts. This is because the pitch measures the distance between screw threads — regardless of whether the threads are of the same start or track.



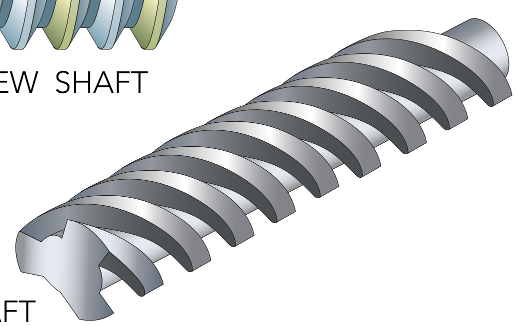
SINGLE-START BALLSCREW SHAFT



QUAD-START SCREW SHAFT



DOUBLE-START SCREW SHAFT



TRIPLE-START BALLSCREW SHAFT

UNCOMMON

For a single-start screw, the lead and pitch are equal. For a multistart screw, the relationship between lead and pitch depends on the number of starts.

Notice that for the single-start ballscrew, there is significant space between the ball tracks. The double-start screw employs that space with an additional independent ball track.

OIL VERSUS GREASE FOR BALLSCREW LUBRICATION

Ballscrews can be lubricated with either grease or oil. Grease is more commonly used for ballscrew lubrication because it doesn't entail complicated delivery methods, and it requires less frequent relubrication intervals. But despite the simplicity of using grease, in many applications, oil lubrication is the better choice for ballscrew assemblies.

First, oil provides cooling and minimizes heat buildup within the ballscrew assembly. Heat causes thermal expansion of the screw shaft, which changes the dimensions of the screw threads and negatively affects positioning accuracy, so reducing heat can be critical in applications that require high speeds or high precision.

Plus, if the oil is circulated through an external lubrication system, the cooling effect of the oil can be significant. Circulation systems also allow for debris to be filtered from the oil, which extends the life of the lubrication and reduces wear on the screw assembly. The drawback is that an external circulation system adds complexity and cost to the assembly.

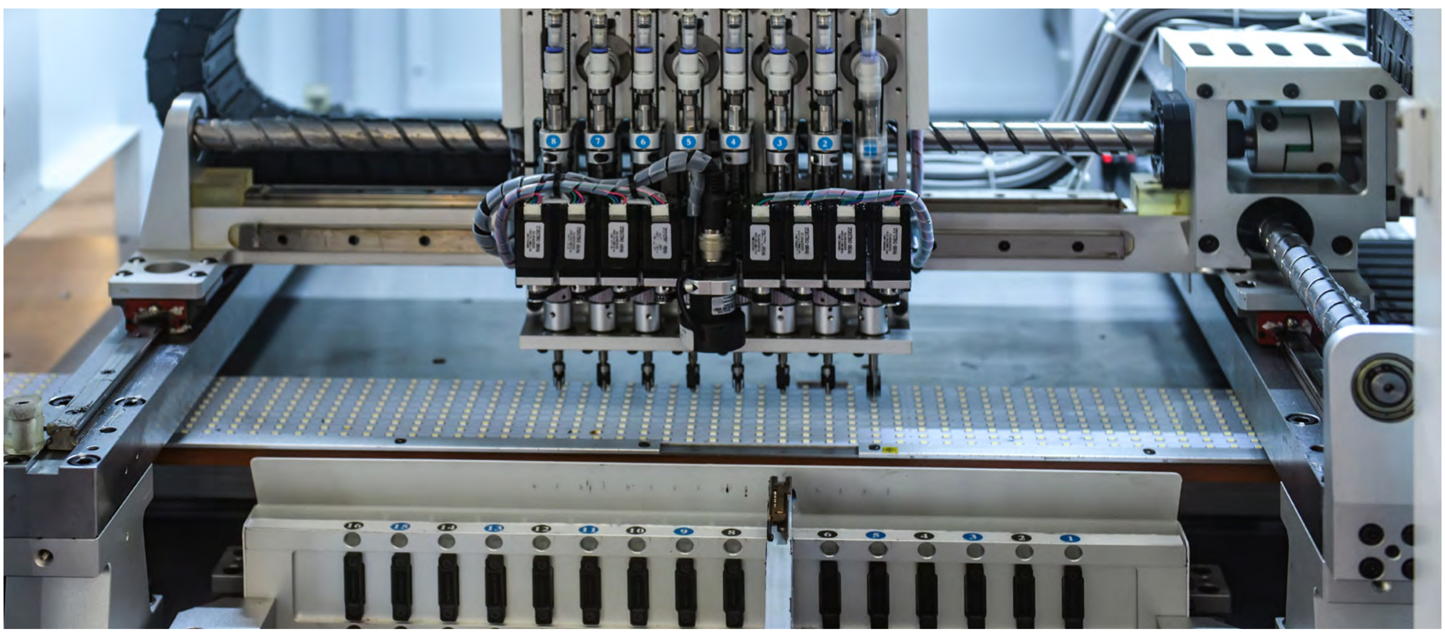
When using oil for ballscrew lubrication, it's important to use the right viscosity oil in the proper amount. If the oil viscosity is too high or if there's too much oil, excessive heat can be generated. On the other hand, if the oil viscosity is too low (or if there's not enough oil lubrication) the screw will experience additional friction and wear will be accelerated. The proper oil viscosity is based on the screw's average speed, diameter, and operating temperature.

If the applied load is high — typically greater than 15 to 20% of the dynamic load capacity — manufacturers often recommend using oil with extreme pressure (EP) additives for extra protection against wear.

With oil lubrication, it's also critical that the application conditions are sufficient to allow an elastohydrodynamic (EHD) lubrication film to form. This film separates the load-carrying balls from the raceways and prevents metal-on-metal contact.

There are three primary conditions that determine whether a lubrication film will develop:

- The lubricant's viscosity
- Screw speed
- Pressure between the balls and shaft raceway.



Manufacturers often provide selection guides to help with choosing the proper oil viscosity for ballscrew lubrication, based on the screw's operating temperature and average speed.

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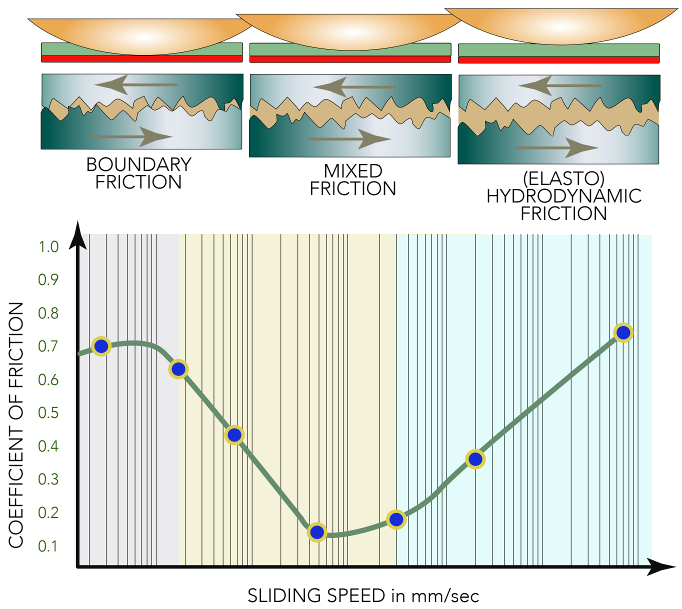
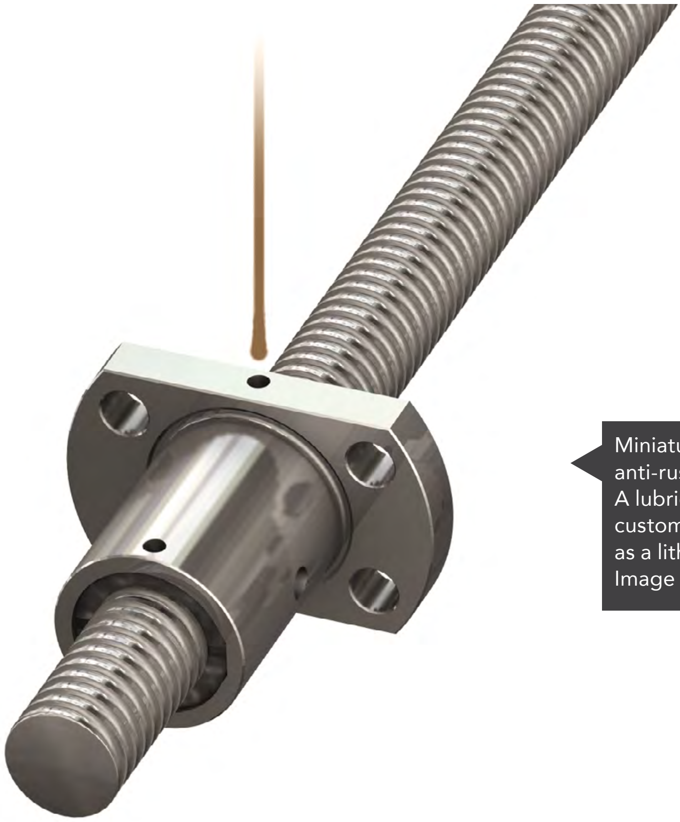
OIL VERSUS GREASE FOR BALLSCREW LUBRICATION

Because of speed's influence on EHD lubrication, low-speed applications generally require grease, which provides better protection under the conditions of boundary lubrication (essentially metal-to-metal contact) or mixed-lubrication (a combination of metal-to-metal contact and lubrication support).

Ballscrews with built-in lubricators typically work by supplying oil directly to the raceways of the screw. This oil supplements grease within the ball nut and extends lubrication intervals significantly, sometimes allowing a screw to operate for several years without relubrication.

Oil with the proper viscosity and in the proper amount will let the ballscrew operate in the region of elastohydrodynamic friction.





Miniature ball screws from PBC Linear ship with anti-rust oil that should be removed before use. A lubricant that fits the specific application and customer preference should then be applied, such as a lithium-based NLGI 2 grease with EP additive. Image Courtesy of PBC Linear

HOW TO PROTECT BALLSCREWS IN HARSH ENVIRONMENTS

CNC milling can generate debris and dirt that can (if not mitigated) quickly damage motion components such as ballscrews. Virtually all seals provide some level of protection against solid contamination such as metal or wood chips, and dust from ceramics or glass.

Harsh environments can wreak havoc on motion system components — especially rolling element systems such as linear guides and ballscrews. While protective devices such as rail covers, wipers, and scrapers are widely available for linear guides, protecting ballscrews in harsh environments is a bit trickier.

But despite being more difficult to safeguard from contamination and temperature extremes, there are measures that can help prevent these environmental conditions from severely shortening the life — or even causing failure — of a ballscrew assembly.

MATERIALS FOR HARSH ENVIRONMENTS

When selecting a ballscrew for an application that involves liquid contamination such as water, acids, or alkaline cleaning solutions, one of the first things to consider is the material of the components — especially the screw shaft, ball nut, and seals.

Although screw shafts and ball nuts are typically made of steel for high load capacity and rigidity, there are other material options that can help them withstand challenging environments. For example, protective coatings such as thin dense chrome, electroless nickel, or black oxide can be applied to the screw shaft and in some cases the ball-nut housing. And some manufacturers offer ballscrew shafts made of stainless steel, for applications where water or chemicals pose a significant challenge.

It's important to note that some coatings can flake, or separate, from the base screw material under extreme loads and pressures … and stainless steel screws have reduced load capacities when compared to their steel counterparts.

Coatings also add a few microns of thickness to the surface and can affect ball-nut preload. It's best to consult with the screw manufacturer when deciding on the best material or coating to determine which option will provide the best defense against environmental hazards — and also to determine its effect on screw performance.

SEALS PROTECT AGAINST SOLID AND LIQUID CONTAMINANTS

Seals located on each end of the ball nut can prevent both liquid and solid forms of contamination from making their way between the load-bearing balls and the raceway. In addition to keeping contamination out, these seals also serve the important function of keeping lubrication in.

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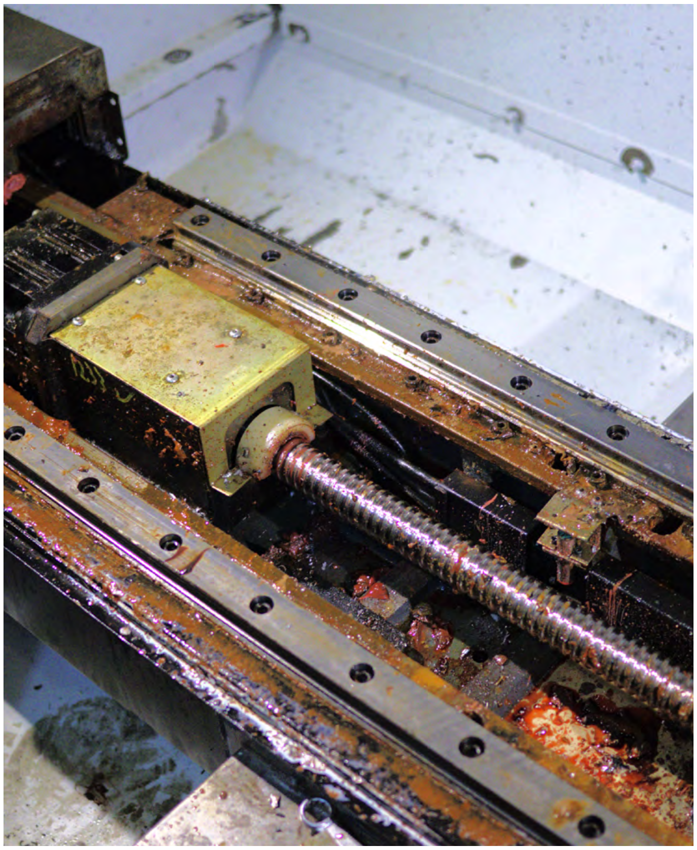
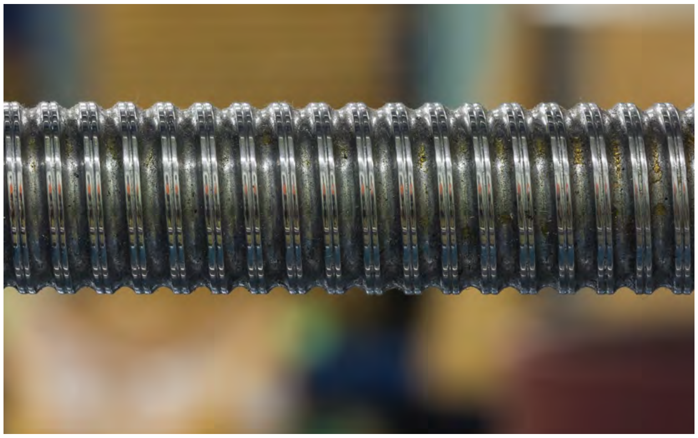
HOW TO PROTECT BALLSCREWS IN HARSH ENVIRONMENTS



If a screw has more than one start, a new ball nut can be assembled onto the unused (and undamaged) screw thread.



This ballscrew shaft is showing evidence of spalling and flaking — possibly resulting from either normal wear or insufficient lubricant.

Ballscrew manufacturers offer a variety of seal types, from felt or brush-type wipers that protect against solid contaminants, to full-contact seals that perfectly match the profile of the screw raceway and prevent virtually any liquid or solid contamination from entering the ball nut.

Standard ball nut seals are commonly made of FKM (Viton) but manufacturers offer other materials, such as EPDM, that can withstand temperature extremes and protect against specific chemicals. Keep in mind that seals that contact the screw shaft — those that prevent small particles and liquids from entering the ball nut — increase friction and drag torque, which must be accounted for during sizing.

TEMPERATURE CAN ALSO BE AN ENVIRONMENTAL HAZARD

The normal operating temperature for ballscrew assemblies depends in part on the type of seals and lubrication used, but generally ranges between 0° C and 80° C. Temperatures higher or lower than these limits, as well as significant temperature fluctuations, can cause thermal expansion of the screw shaft. Case in point: A 1° C rise in temperature can cause the screw shaft to lengthen by 0.012 mm per meter of length. As the screw lengthens, the lead of the screw thread elongates, which reduces the screw's accuracy.

One method to mitigate the effects of thermal expansion is to mount the screw shaft in tension, with fixed bearings on both ends. This helps to prevent the screw from expanding (or contracting) due to heat (or cold). Forced air cooling of the screw assembly is also a good solution in some applications. A more extreme measure (but one commonly used in applications such as machine tools, where travel accuracy is critical) is to use a **hollow screw shaft** with internal cooling to reduce the temperature of the screw material.

But it's not just the effect of temperature on the screw shaft that needs to be considered. In fact, virtually every part of the screw assembly can be affected by temperature extremes. As mentioned above, materials for seals can be chosen to meet specific temperature requirements. End bearings also have seals with specific temperature ratings, so the permissible operating temperature of the end bearings should be checked as well.

(continued)

HOW TO PROTECT BALLSCREWS IN HARSH ENVIRONMENTS

Temperature extremes can even affect the performance of lubrication because the lubricant's viscosity (resistance to flow) is determined in part by its temperature. Plus, every lubricant has strict temperature limits to ensure that it doesn't separate into its components of base oil, thickener, and additives … so it's important to check the lubricant's operating temperature range as well.

TIPS AND BEST PRACTICES FOR DESIGN

There are a few best practices that can help when designing ballscrews for harsh environments. The most fundamental of these is to mount the ballscrew away from areas that are highly susceptible to contamination. Also, mounting the screw above the work area can often reduce the amount of contamination to which the screw is exposed.

If particulate contamination is significant and can't be avoided, bellows covers can protect against some liquids and most falling particles. And in cases where even the most stringent protective measures may not be sufficient, using a multi-start screw can reduce maintenance time and cost if wear or failure does occur by allowing a new ball nut to be assembled onto the unused (and hopefully undamaged) screw thread.

Additional reading:

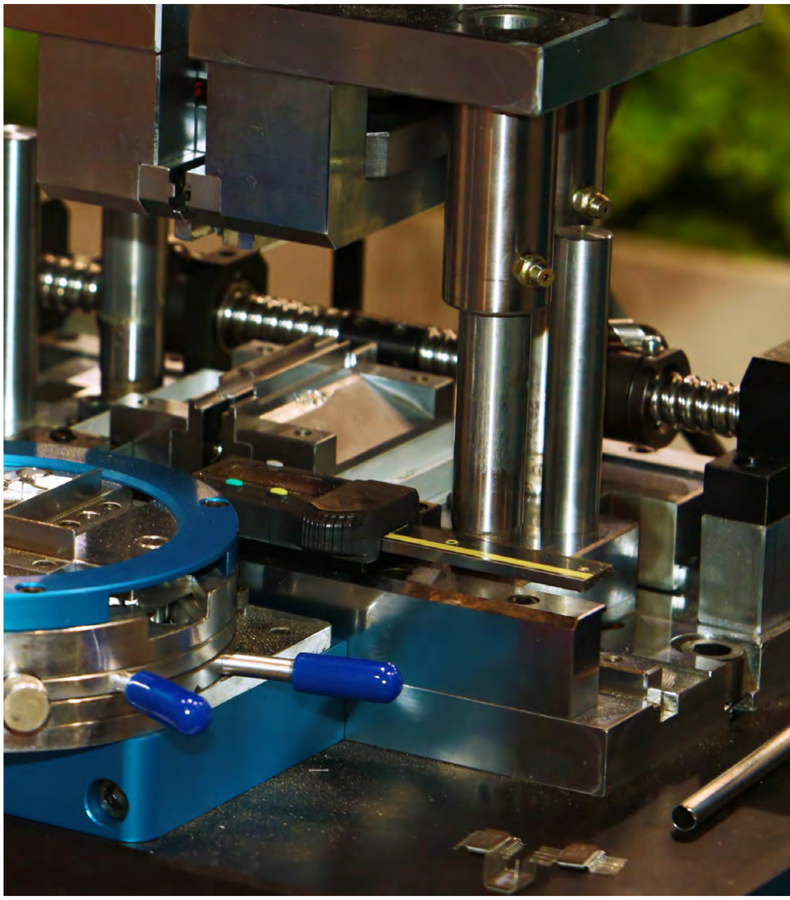
Accounting for shock and vibration in ballscrew drives

Types of seals for ballscrews compared

How temperature affects ballscrew-based assemblies

Designing ballscrew-based designs for long strokes

Selecting ballscrews for miniature designs



Mounting a ballscrew in tension with fixed bearings on each end can help mitigate thermal expansion.

PBC Linear utilizes polymer wipers located at each end of their multiliner return (short lead) nut to prevent the ingress of debris and particulates. End-cap return (long lead) nuts allow for similar resistance in contaminated environments. Image Courtesy of PBC Linear

COMPARING DIN, ISO, AND JIS BALLSCREW STANDARDS

Shown here is a precision screw-based drive in a scanning electron microscope (SEM).

If you're involved in ballscrew sizing or selection, you've probably noticed that there are several different standards that govern various aspects of ballscrew design, from lead accuracy and load capacity to ball nut tolerances and rigidity. Fortunately in many cases these standards are in harmony and provide the same (or virtually equivalent) specifications.

But in the areas where the standards diverge and the specifications differ, it can be difficult for engineers and designers to compare products and choose the ballscrew that meets their design and application requirements. So until the industry comes together and adopts a single, international standard, here's a guide to the similarities and differences between the most commonly used ballscrew standards: DIN, ISO, and JIS.

GERMAN INSTITUTE FOR STANDARDIZATION • DIN INTERNATIONAL ORGANIZATION FOR STANDARDIZATION • ISO

Originally two separate standards DIN 69051 and ISO 3408, the DIN and ISO ballscrew standards have been mostly combined and harmonized. The harmonized standard is called DIN ISO 3408, which means the ISO standard has been adopted directly as the DIN standard.

The DIN ISO 3408 standard consists of four sections:

DIN ISO 3408-1: Ballscrews – Part 1: Vocabulary and designation

DIN ISO 3408-3: Ballscrews – Part 3: Acceptance conditions and acceptance tests

DIN ISO 3408-4: Ballscrews – Part 4: Static axial rigidity

DIN ISO 3408-5: Ballscrews – Part 5: Static and dynamic axial load ratings and operational life

Notice that Part 2 of the ISO standard has not been adopted as a DIN standard, and each retains its own designation — in other words, DIN 69051 Part 2 and ISO 3408-2. In both standards, Part 2 defines nominal diameters and leads, so the variation between ISO and DIN means they allow for some differences in the available diameter and lead combinations (d0 x P).

DIN 69051-2: Machine tools; ballscrews; nominal diameters and nominal leads (1989)

ISO 3408-2: Ballscrews: Nominal diameters and nominal leads – Metric series (1991)

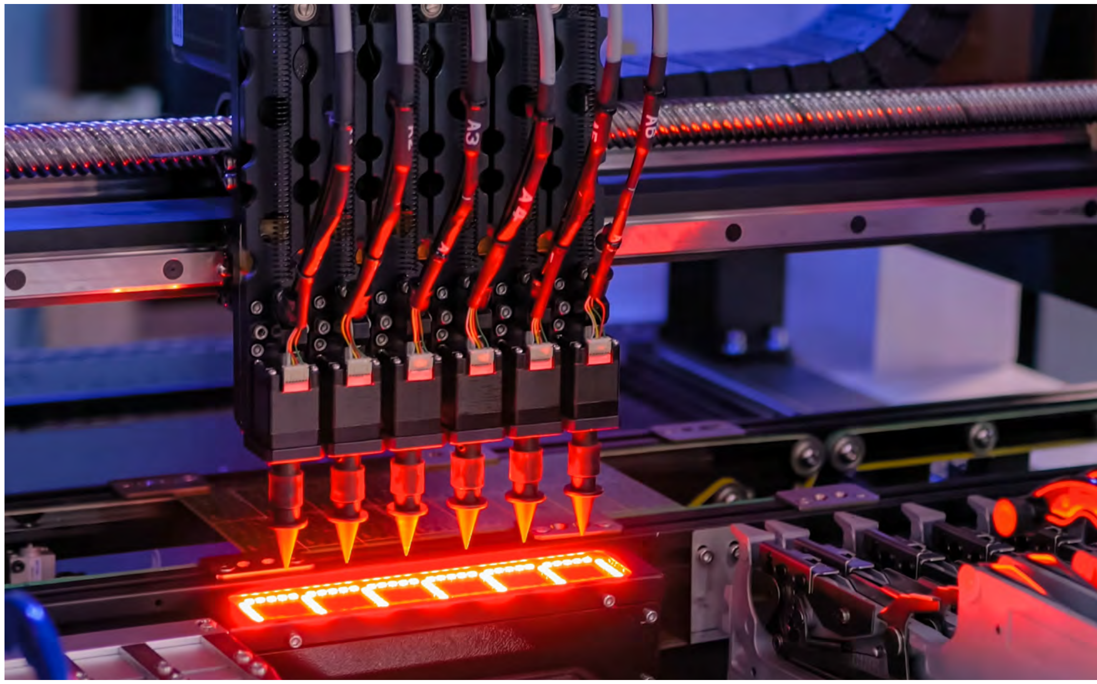
(continued)

COMPARING DIN, ISO, AND JIS BALLSCREW STANDARDS

JIS (JAPANESE INTERNATIONAL STANDARD)

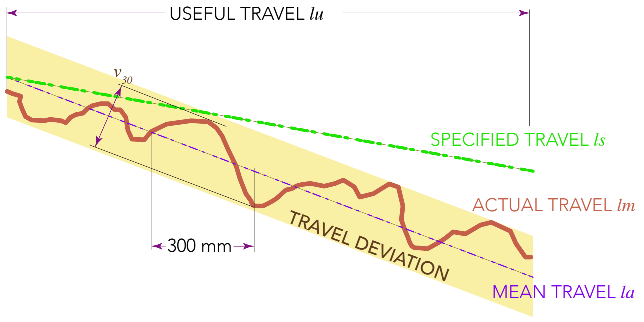
Another common ballscrew standard is JIS B1192-1997. (Note that JIS B1191 is sometimes referenced, but it was replaced by **JIS B1192** in 1997.) JIS B1192-1997 is like DIN ISO 3408, but there are some noticeable differences.

First, there are variations between the DIN ISO standard and JIS B1192-1997 regarding the travel deviation specifications v300 and vu. In addition, JIS uses accuracy class designations of C for positioning screws and Ct for transport screws, whereas the DIN ISO standard uses the designations P for positioning screws and T for transport screws. The JIS B1192-1997 standard also includes several accuracy classes that DIN ISO 3408 doesn't address.



The JIS B1192-1997 and DIN ISO 3408 ballscrew standards provide different permissible travel deviation values for some (but not all) accuracy classes.

Other variations between JIS B1192-1997 and DIN ISO 3408 can be found in the dimensional tolerances and run-out specifications of the screw and nut, and in the permissible torque fluctuations of preloaded nuts. But these variations typically occur only in certain instances within a given specification — not across the entire range of products. For example, JIS B1192-1997 and DIN ISO 3408 specify different v300 travel deviation limits for screws in accuracy classes 3 and 5, but they provide the same v300 specification for class 7 screws.



Note the screw-driven axis in this precision SMD pick-and-place machine for electronics assembly.

Examining the specifications of a ballscrew manufactured to the JIS B1192-1997 standard will reveal exceptions — for which ballscrew manufacturers have deviated from the JIS standard. In many cases, the manufacturer's deviation provides a better tolerance or more stringent acceptance criteria. But it is nonetheless a deviation from the standard.

Some in industry regard DIN ISO 3408 to be a standard requiring rigid adherence, and the JIS B1192-1997 standard as more of a suggestion for ballscrew manufacturers.

(continued)

COMPARING DIN, ISO, AND JIS BALLSCREW STANDARDS

The JIS B1192 standard that we've discussed so far is the 1997 publication (JIS B1192-1997) but it isn't the most recent version. JIS B1192 was updated in 2013 (JIS B1192-2013) to conform with the ISO 3408-1, 2, and 3 specifications for ballscrew definitions, nominal diameters and leads, and acceptance conditions. Another update was just published in August 2018 (JIS B1192-2018) harmonizes the JIS standard with ISO 3408-4 and ISO 3408-5 specifications for axial rigidity and static and dynamic load ratings.

> *In a sign that the ballscrew industry is moving toward a single international standard, manufactures who historically offered only JIS or only DIN ISO ballscrews are beginning to add products that are compliant with the other standard.*

Manufacturers of JIS ballscrews still cite the 1997 version (JIS B1192-1997) in their specifications, but they will likely begin citing the more recent 2013 version (or even the 2018 version) in the not-too-distant future, as they comb through the changes and adjust specifications to be compliant with ISO 3408.

Because the variances between JIS B1192-1997 and ISO 3408 are generally quite small, the switch from the 1997 version to either of the updated JIS standards isn't likely to be a major disruption to customers who use JIS-standard ballscrews. The most noticeable difference will probably be in the form of dynamic load capacity changes.

JIS-standard ballscrew manufacturers underscore that the method for determining dynamic load capacity is the most significant difference between ISO 3408 and JIS B1192-1997. So it's likely that the published dynamic load capacities of JIS-standard ballscrews will undergo a change as manufacturers re-rate their products to meet the ISO specification.

In summary, while the changes in load ratings may catch some users off guard or cause a bit of confusion for a short time, some in the motion industry assert that ballscrew standards were destined to eventually come together. After all, competition in the field of automation is hard enough — and (at least some believe) the industry needs a single international standard.

Additional reading:

[Deeper dive on ANSI and ISO ballscrew load capacities]

[Ball conformity in ballscrews]

[Quantifying ballscrew lead error]

WHAT IS BALLSCREW WHIP AND WHY DOES IT HAPPEN?

Ballscrews are often the drive mechanism of choice in applications that require high thrust forces with excellent positioning accuracy and repeatability. But one of the drawbacks of ballscrew technology is that speed is inversely related to length … so the longer the ballscrew shaft, the more likely it is to whip like a jump rope as it turns. This behavior limits the maximum travel distance that can be achieved when high speeds are necessary and vice-versa.

WHAT IS CRITICAL SPEED?

The permissible operating speed of a ballscrew assembly depends on two parameters — critical speed and characteristic speed. Characteristic speed is determined by factors related to the ball nut, including the ball return system and the mass of the balls. However, improvements in ball nut manufacturing and ball recirculation methods have provided most ballscrew assemblies with very high characteristic speeds, so the limiting factor is typically the critical speed.

For a rotating shaft, such as a ballscrew assembly, critical speed is defined as the angular velocity that excites the natural frequency, or first resonant frequency, of the assembly. If the shaft is operated at its natural frequency, it can begin to resonate, causing severe damage — or even destruction — to the assembly.

Gumpanat Thavankitdumrong · Dreamstime

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WHAT IS BALLSCREW WHIP AND WHY DOES IT HAPPEN?

WHY DO BALLSCREWS EXPERIENCE RESONANCE?

In theory, a shaft could be perfectly balanced — that is, its mass is perfectly distributed about its volume. Upon rotation of such a perfect component, there is no bending of the shaft, and the center of mass lies along the axis of rotation.

In the real world, even the most precisely manufactured and machined shafts are not perfectly balanced — so the center of mass is very slightly offset from the axis of rotation. In addition, because the screw shaft is supported only at its ends, it bends somewhat under its own weight, moving the center of mass even farther from the axis of rotation. As the ballscrew shaft rotates, the discrepancy between the center of mass and the axis of rotation produces centrifugal forces, which cause the shaft to deflect or whip like a jump rope.

If this vibration or ballscrew whip approaches or reaches the natural frequency of the screw shaft, resonance can ensue and lead to increased noise, damage, and in extreme cases yielding of the shaft. Click here for details on how to calculate ballscrew critical speed.

It's important to remember that if the ball nut is preloaded, the unsupported length is based on the greatest distance between the ball nut and the end of the screw that will occur in operation. For non-preloaded ball nuts, the unsupported length is simply the length between bearings. Also note that some manufacturers include a safety factor of 0.8 when determining the value of non-variable factors influencing critical speed, because it's generally recommended that a ballscrew not be operated at more than 80% of its critical speed. Standard equations don't include this 0.8 safety factor, so engineers should verify whether the ballscrew manufacturer has included it in their published values, or if it needs to be included during calculation.

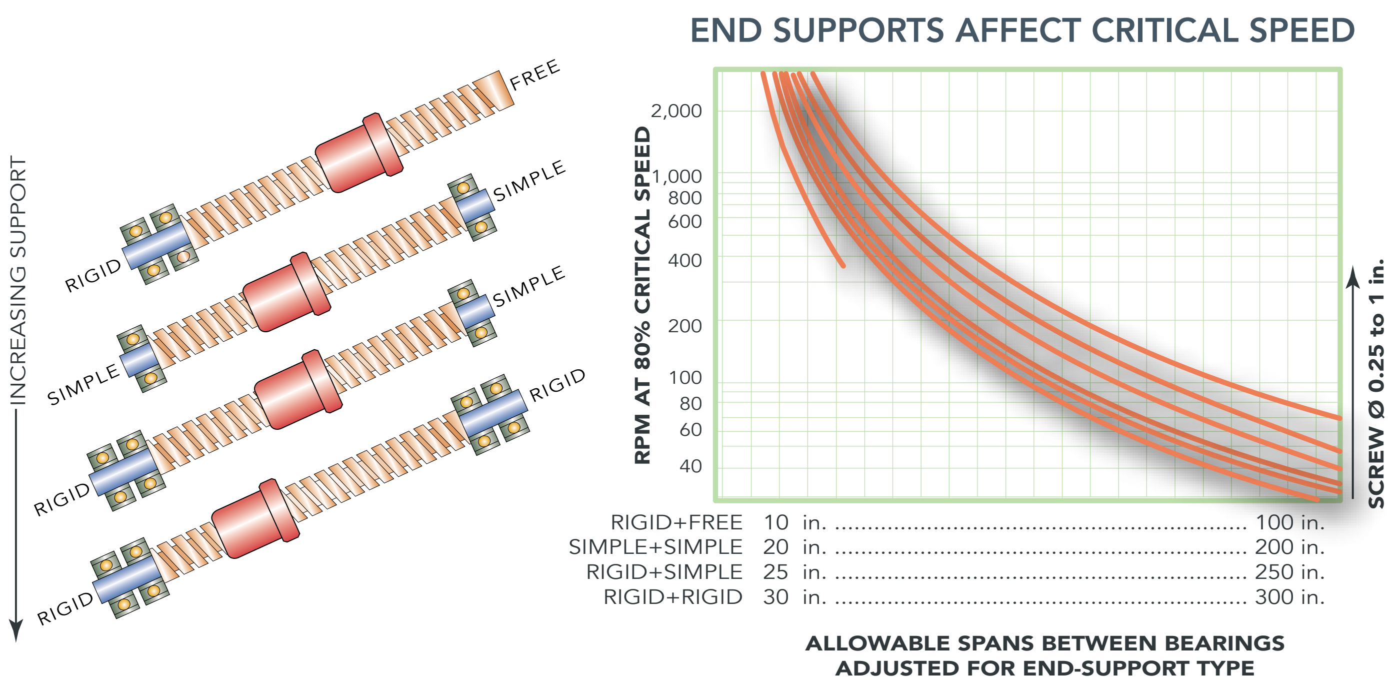
Additional reading:

Pairing steppers with ballscrews instead of leadscrews

The use of ball chains in ballscrews and guides

Ballscrew characteristic speed versus critical speed

Accounting for ballscrew inertia during system design



As a ballscrew shaft rotates, it begins to whip – much like a jump rope. This behavior limits the screw's critical speed.

WHAT MAKES MINIATURE BALL SCREWS UNIQUE?

Ball screws are used in a wide variety of applications, but some of the most challenging are those on the extreme ends of the performance spectrum – from large diameter, large lead screws for machine tools, to screws with small diameters and very fine leads for optical and medical applications. For very small, high-precision movements, designers and engineers often turn to miniature ball screws.

While there's no industry standard for what classifies a screw as "miniature," most manufacturers apply the designation to screws with a diameter smaller than 16 mm, while others include 16 mm screws in their "miniature" product line. To further segment the range of sizes, screws with a diameter smaller than 6 mm are sometimes referred to as "sub-miniature" or "ultra miniature."

Ball screws with a diameter smaller than 16 mm are typically referred to as "miniature," while screws with a diameter smaller than 6 mm are often termed "sub-miniature" or "ultra miniature." Image credit: August Steinmeyer GmbH & Co.

Some manufacturers offer a "compact" range of ball screws. This term generally indicates that the ball nut uses internal recirculation, giving it a smaller outer diameter. (Hence, the term "compact.") Despite their name, compact designs often include screws with diameters up to 25 mm – much larger than traditional "miniature" ball screws.

In some regards, miniature ball screws are the same as their larger, "standard" counterparts. For instance, miniature ball nuts are offered in many of the same styles as standard ball nuts, including flanged, cylindrical (also referred to as "compact" or "slim"), or with a threaded end for easy mounting into a carriage or table assembly. Ball recirculation can be done inside the ball nut or with external recirculation methods. Lead accuracies and preload classes follow the same designations regardless of the screw diameter. And sizing parameters, such as L10 life calculation, buckling load, and critical speed, are the same for both miniature and standard ball screws.

Miniature ball screws, like standard versions, can be manufactured by either rolling or grinding the screw threads. Screw diameters below 8 mm are commonly produced by grinding, although some manufacturers offer screws as small as 6 mm diameter in rolled versions. In some miniature screw sizes, the journal diameter of the screw is too small to accommodate an appropriately sized end bearing. To address this, manufacturers can friction weld a larger journal onto the screw end, providing a sufficient journal for the support bearing.

Miniature ball screws often use friction welded ends to accommodate journal machining and support appropriately sized end bearings. Image credit: The Precision Alliance

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WHAT MAKES MINIATURE BALL SCREWS UNIQUE?

In addition to small screw diameters, miniature screws offer an advantage over standard versions with their option for very fine leads. The smallest miniature screws have a lead of just 0.5 mm, which means every rotation of the screw produces 0.5 mm of travel. This is a significant benefit in applications that require fine adjustments, such as positioning semiconductor wafers or optical equipment, or driving small medical pumps and dispensing equipment.

Because miniature screws use very small balls for load carrying, preload options are more limited, with only a light preload of 1 to 2 percent typically achievable, versus up to 5 percent with standard ball screws using the oversized ball preload method. However, miniature screws offer more customization options and more standard variations in some respects. For example, combination left- and right-hand screws (where one segment of the screw has left-handed threads and another segment has right-handed threads) are commonly available in miniature designs.

Screws and nuts made from stainless steel are also readily available in miniature screw offerings, where they are rarely available for standard sizes. This can be attributed to the fact that miniature screws typically carry smaller loads, whereas stainless material would not be able to withstand the high loads that larger ball screws often transport.

Due to their small leads, miniature ball screws can execute very fine movements, and in vertical applications, these small leads make backdriving nearly impossible. Because ball screws operate with metal-to-metal contact, they're not good for oscillating applications, even in miniature sizes where stroke lengths are typically small. For applications with oscillating-type motion, voice coil or piezo actuators may be a better choice.

PBC Linear offers high-precision, miniature metric ball screws in diameter sizes of 6, 8, and 10 mm, with a variety of lead lengths. Image Courtesy of PBC Linear