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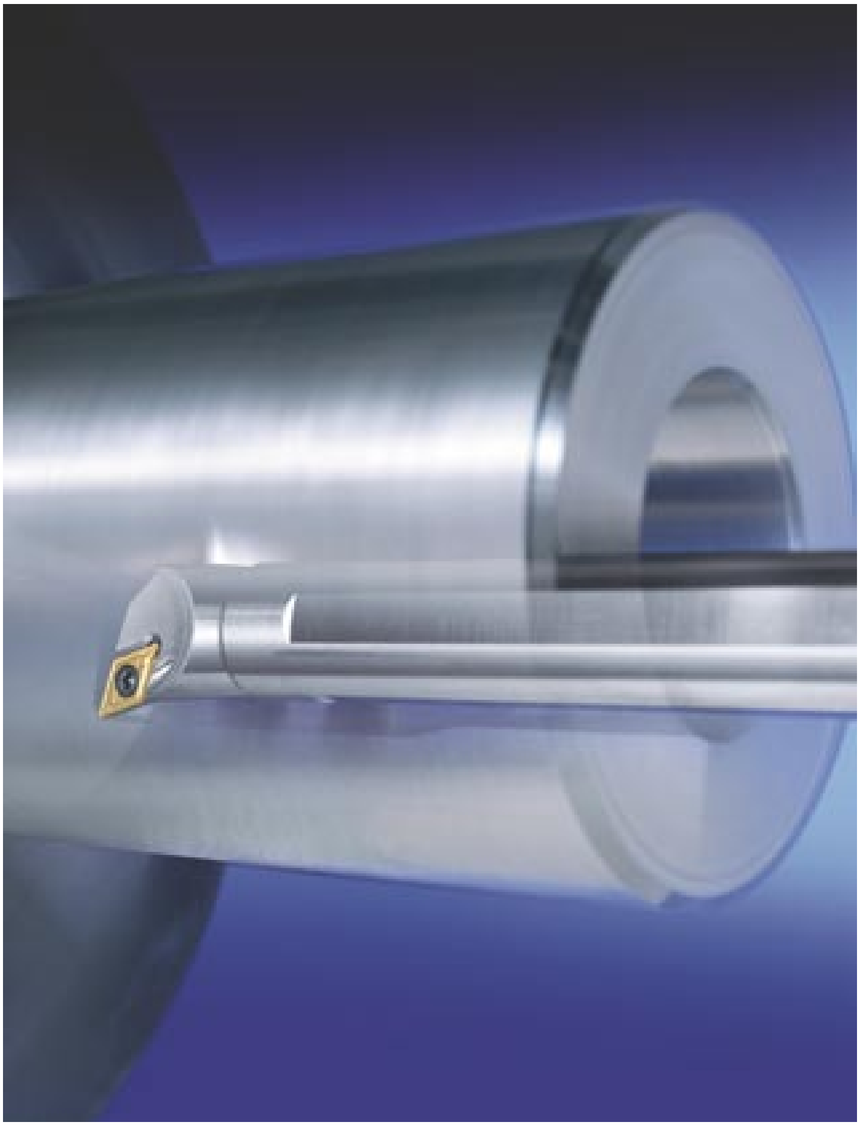
Boring: The Inside Scoop

Metalcutting expert explains the fundamentals of boring.



Kyocera Industrial Ceramics/Ceratip

Much has been written about boring, some of it excellent and some of it flat-out wrong. The myths and fallacies must be dispelled to effectively perform this critical hole-finishing operation.

Boring is an internal turning operation in which cutting tools enlarge holes or other circular contours. Boring operations typically range from semiroughing to finishing. Single-point cutting tools, known as boring bars, are commonly used.

A boring bar has three basic elements: an indexable insert, a shank and an anchor (Figure 1). The anchor is the clamping portion of the shank. Typical clamping length is about four times the diameter of the shank. The length by which a shank with an insert extends from the anchor is the overhang (the unsupported portion of the bar).

The overhang determines the maximum depth of the bore and is the most important dimension of a boring bar. Too long of an overhang causes excessive deflection of the shank, can cause chatter (which deteriorates the surface quality of the workpiece) and may cause premature insert failure. All of these reduce machining efficiency.

For most applications, end users should choose a boring bar with the highest static and dynamic stiffness. Static stiffness is a bar's ability to resist deflection from the cutting force, and dynamic stiffness is a bar's ability to dampen vibration.

The first portion of this article focuses on static stiffness of boring bars. The information was extracted from the author's analytical study of boring bar deflection, which depends on mechanical properties of the shank material and shank dimensions and the cutting conditions.

Cutting Force

The cutting force acting on the boring bar can be measured using a turning dynamometer. Three components are measured: tangential force, feed force and radial force. Compared to the other two forces, tangential force is the largest by magnitude.

The tangential force acts perpendicular to the insert's rake face and pushes the bar below the centerline—downward. It is important to note that tangential force is applied near the nose of the insert, not to the centerline of the shank. The shift from the centerline creates the arm—the distance from the centerline to the applied force—for tangential force. That produces torque, which causes torsional deflection of the bar about its centerline.

Feed force is the second largest by magnitude. Feed force is exerted parallel to the centerline of the shank and does not deflect the boring bar. Radial force is exerted perpendicular to the centerline of the shank and pushes the bar away from the bore surface.

Thus, only tangential and radial cutting forces deflect the boring bar. For decades, the rule of thumb was that the magnitudes of feed and radial forces were about 50 and 25 percent of the tangential force, respectively. Such proportions are not considered "best practice" today, because the relationship between these cutting forces depends on the specific workpiece material, its hardness, cutting conditions and the insert's nose radius. The following formula is recommended to calculate tangential force (F_t):

F_t = 396,000 × DOC × feed rate × power constant

The resultant force (F) deflecting the boring bar is calculated by the formula:

$$F = \sqrt{F_t^2 + F_r^2}$$

where F_r is radial force.

Deflection of Boring Bars

Boring bar deflection is similar to that of a beam with a fixed support at one end (a clamping portion, or anchor) and an unsupported portion, or overhang, at the other end. Such a beam is called a cantilever beam. Because of the similarity, the formula describing a cantilever beam's deflection (y) is applicable to calculate a boring bar's deflection:

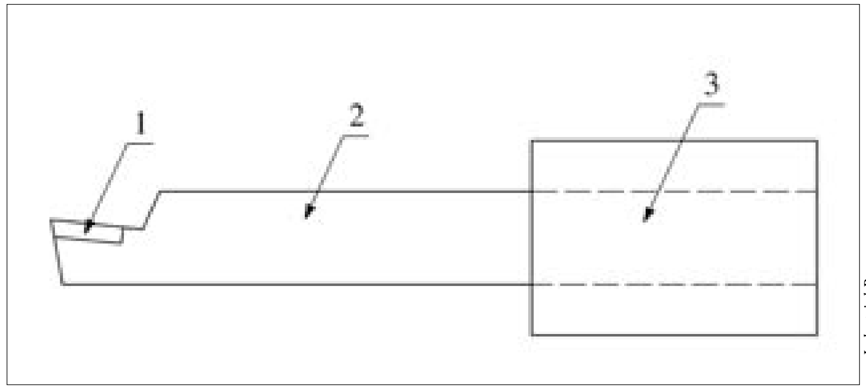


Figure 1: Three basic elements of a boring bar: an indexable cutting insert (1), a shank (2) and an anchor (3).

$$y = \frac{(F \times L^3)}{(3E \times I)}$$

where F = a resultant force; L = overhang, in inches; E = modulus of elasticity (or Young's modulus of a bar material) in psi; and I = bar's cross-sectional moment of inertia, in inches^4.

A boring bar's cross-sectional moment of inertia is calculated by the formula:

$$I = \frac{\pi \times D^4}{64}$$

where D = bar OD, in inches.

Analyses of formulas for calculating a boring bar's deflection and its cross-sectional moment of inertia make it obvious that the following practices should be adhered to when boring:

■ Boring bar overhang should be as short as possible. As the overhang gets longer, the amount of deflection increases. For example, an increase in overhang by 1.25 times almost doubles the amount of deflection ($1.25^3 = 1.95$) if the bar OD and cutting parameters remain unchanged.

■ Boring bar diameter should be as large as possible. As the diameter of a bar gets larger, the moment of inertia of a bar's cross section increases and deflection decreases. For example, an increase in diameter by 1.25 times decreases the amount of deflection by almost 2.5 times ($1.25^4 = 2.44$) if the overhang and cutting parameters remain unchanged.

■ The higher the modulus of elasticity of the boring bar material, the less the amount of deflection if the overhang, bar OD and cutting parameters remain unchanged.

Boring Bar Materials

Boring bar shanks are made of steels, tungsten-base heavy metals and cemented carbides. Alloy steels are the most popular material, but some bar manufacturers use AISI 1144 free-machining carbon steel. Regardless of the grade, all carbon and alloy steels have the same modulus of elasticity, E = 30 × 10^6 psi. A common mistake is to assume that a steel shank with a higher hardness or one made of a higher quality of steel will deflect less. As can be seen from the formula for calculating deflection, one of the variables that determines deflection is modulus of elasticity—not hardness.

Tungsten-base metals are produced by a powder-metallurgy technique. High-purity metal powders—tungsten, nickel, iron and copper—are typical elements for sintering a variety of alloys, some of which are used to fabricate boring bars and other toolholders. Typical tungsten heavy alloys for bars are: K1700 (E = 45 × 10^6 psi), K1800 (E = 48 × 10^6 psi) and SD175 (E = 48 × 10^6 psi). Bars made of these grades deflect 50 to 60 percent less than steel bars of the same diameter and overhang when boring at the same cutting parameters.

Boring bars made of cemented carbides provide the least deflection because their moduli of elasticity are significantly higher than those of steels and tungsten heavy alloys. Typical carbide grades for bars contain 90 to 94 percent tungsten carbide and 10 to 6 percent cobalt, respectively. By industry code definition, such grades may come from the C-1 (E = 82 × 10^6 to 84 × 10^6 psi), C-2 (E = 85 × 10^6 to 87 × 10^6 psi) or C-3 (E = 89 × 10^6 psi) group.

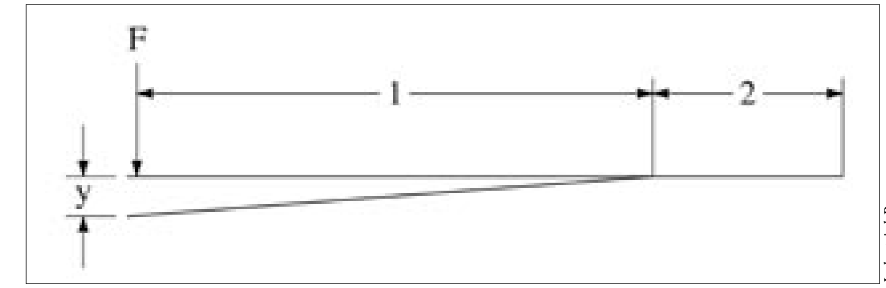
Insert Materials and Geometry

Inserts for boring are made of a variety of cutting tool materials: cemented carbides, ceramics, cermets, PCD and PCBN.

Cemented-carbide inserts are predominantly coated by either the physical-vapor-deposition or chemical-vapor-deposition process. Examples of PVD coatings are TiN, which is suitable for machining high-temperature alloys and austenitic stainless steels, and TiAlN, which is widely used for most steels, titanium alloys, cast irons and nonferrous alloys.

These two types of coatings are applied to carbide substrates, which exhibit high thermal deformation resistance and DOC notch resistance. Such substrates contain about 94 percent tungsten carbide and 6 percent cobalt. They may come from C-3 and C-4 groups by industry code definition, which are equivalent to ISO groups K-10 to K-20, M-10 to M-25 and P-10 to P-20.

CVD-coated carbide grades are used for machining most steels and cast irons. CVD coatings are multilayered compositions of TiN, aluminum oxide, TiCN and TiC. Each layer provides a



Deflection of a boring bar (y) caused by cutting force (F). The overhang = 1; anchor = 2.

specific property, and certain combinations resist different wear mechanisms. Typical carbide grades are multicarbide compositions of tungsten carbide, tantalum carbide and TiC bonded with cobalt. Such grades are within C-1 to C-4 and C-5 to C-7 groups by industry code definition, or K-10 to K-30, M-10 to M-45 and P-05 to P-45 groups by ISO definition.

Ceramic inserts are available in alumina-based (Al_2O_3) and silicon-nitride-based (Si_3N_4) grades. Alumina-based ceramics are available in uncoated grades and PVD TiN-coated grades. Uncoated grades exhibit enhanced toughness and wear resistance. They are recommended for boring alloy steels, tool steels and martensitic stainless steels hardened up to 60 HRC. Coated grades are used for finishing hardened steels, cast irons (45 HRC and harder) and nickel-base and cobalt-base alloys.

Silicon-nitride-based ceramics are available in two-layer CVD-coated grades, with a layer of TiN and a layer of Al_2O_3, and uncoated grades. Coated grades offer a great combination of toughness and edge-wear resistance. They are recommended for machining gray and ductile cast irons. Some uncoated grades provide excellent thermal shock resistance and fracture toughness, and others absorb mechanical shocks and provide edge-wear resistance. These types of grades are for machining high-temperature alloys. Uncoated grades with maximum toughness are recommended for roughing and interrupted machining of gray cast iron.

Cermet combines a ceramic material and a metallic binder. Cermets are titanium-based cemented carbides with a nickel and cobalt binder. Cer-mets are available as coated and uncoated grades. Uncoated grades are hard and feature high resistance to built-up edge and plastic deformation. They are used for finishing of alloy steels when a fine surface quality is required. Multilayered PVD-coated grades, with a layer of TiCN sandwiched between layers of TiN, are applied for high-speed finishing and semifinishing of most carbon, alloy and stainless steels. They also perform well when machining gray and ductile cast irons, providing long tool life and imparting a fine surface finish.

PCD is an extremely hard material produced from diamond particles, a binder and a catalyst under high pressure and temperature. A PCD tip is brazed onto a carbide substrate to form an insert. The most effective application of PCD tools is machining hypereutectic aluminum alloys (silicon content exceeds 12.6 percent). With PCD,

Calculation

Example of a calculation of boring bar deflection.

Given: AISI 1045 carbon steel workpiece (250 HB) to be machined at a DOC of 0.100" and feed rate of 0.008 ipr using a 1.0"-dia. steel boring bar (E = 30 × 10^6 psi) with unsupported overhang of 4.0".

Required: Amount of deflection.

1. Tangential force calculation
   F_t = 396,000 × DOC × feed rate × power consumption =
   396,000 × 0.1 × 0.008 × 0.99 = 313.6 lbs.
2. Radial force calculation
   $F_r = 0.308 \times F_t = 0.308 \times 313.6 = 96.6$ lbs.
3. Resultant force calculation
   $F = \sqrt{F_t^2 + F_r^2} = \sqrt{313.6^2 + 96.6^2} = 328.1$ lbs.
4. Moment of inertia calculation
   $I = \frac{\pi \times D^4}{64} = \frac{\pi \times 1^4}{64} = 0.0491$ in.^{4}
5. Deflection of boring bar calculation
   $y = \frac{(F \times L^3)}{(3E \times I)} = \frac{(328.1 \times 4^3)}{(3 \times 30 \times 10^6 \times 0.0491)} = 0.0048$"

(Adopted from Industrial Press' Engineering Formulas for Metalcutting, *pp. 154-156.)*

the cutting edge remains sharp longer than any other tool material. PCD tools can operate at high cutting speeds.

PCBN ranks next to PCD on the hardness scale. A variety of PCBN-tipped carbide inserts with small or large tips, solid-PCBN inserts and full-face PCBN inserts backed with tungsten carbide are available. Common applications for PCBN grades include finishing of hardened steels, tool steels and HSS (45 to 60 HRC); gray and chilled cast irons; and sintered powdered metals. A distinctive feature of PCBN is that its room-temperature hardness is practically the same as its hot hardness in the cut. Such a phenomenon results in longer tool life at significantly higher cutting speeds than when machining similar workpiece materials with other types of cutting tools.

Concerning the geometry of the inserts, insert types for steel shanks are: CNMG 332, CNMG 432 and CNMG 542; DNMG 332 and DNMG 442; SNMG 432; TNMG 332 and TNMG 432; VNMG 332 and VNMG 432; and WNMG 332 and WNMG 432. Principal insert angles are rake, inclination and lead. Rake and inclination angles are negative. Typical rake angle is -6°. Inclination angles are mainly from -10° to -16° and vary with the shape of inserts. Lead angles relate to the shape of inserts: -5° for CNMG and WNMG; -3° for DNMG and VNMG; -1° for TNMG and 15° for SNMG.

Workpiece materials	Brinell hardness	Radial force formula
Carbon, alloy, stainless and tool steels	80 to 250	$F_r = 0.308 \times F_t$
Carbon, alloy, stainless and tool steels	250 to 400	$F_r = 0.672 \times F_t$
Ductile and gray cast irons	150 to 300	$F_r = 0.331 \times F_t$

Radial force (F_r) vs. tangential force (F_t).

When an end user carefully balances the combination of insert material and geometry, boring bar material and cutting force, boring bar deflection is minimized and hole specifications are met. △

About the Author

Edmund Isakov, Ph.D., is a consultant and writer. He is the author of several books, including Engineering Formulas for Metalcutting *(Industrial Press, 2004) and* Advanced Metalcutting Calculators *(Industrial Press, 2005).*