DETECTING AND CORRECTING UNBALANCE IN TOOLHOLDERS FOR HIGH SPEED MACHINING

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ABSTRACT

Over the past ten years we have witnessed a revolution in metalcutting in the field of High Speed Machining. As machining speeds continue to increase, particularly spindle RPM, forces created by unbalance in the spindle, cutting tool, and toolholder require close attaention. It has been observed that these forces, if left uncompensated, can result in poor surface finish, loss of tool life, and spindle bearing failure. The sources of this unbalance needs to be identified and elimated in order to create a smooth, vibration free condition and allow the machine tool and its spindle to operate properly.

Key Words: High Speed Machining, Spindle, Toolholder, Cutting Tool, Centrifugal force, Unbalance

1.Introduction

The purpose of this discussion is to examine the relationship between unbalance and toolholders used in high speed metalworking machine tools. In order to effectively present this information, four topics must be explored:

- the effects of unbalance
- the sources of unbalance
- methods of correction
- determining balance tolerance

Before we proceed with the discussion of these topics however, perhaps a short review of the principles of balance theory would be beneficial.

2. Definition of Unbalance

Unbalance can be defined as the condition which exists when the principle mass axis of a rotating body, also known as the "Axis of Inertia", does not coincide with the rotational axis.

There are three principle types of unbalance which are encountered:

- Static Unbalance
- Couple Unbalance
- Dynamic Unbalance

2.1 Static Unbalance

Static Unbalance is present in a rotor when the mass axis does not coincide with the rotational axis and is parallel to the rotational axis. This is also known as "single plane" unbalance. As can be seen in Figure 1, the force created by this unbalance is equal in magnitude at both the bearing journals, and the angular position of the force vector is also the same at both the bearing journals.

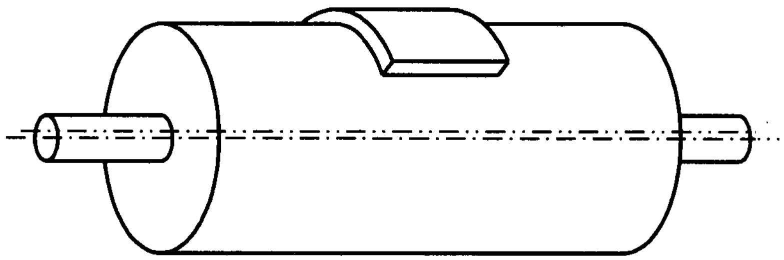


Figure 1

2.2 Couple Unbalance

Couple Unbalance is present when the mass axis does not coincide with the rotational axis, but does intersect the rotational axis at the center of gravity of the rotor. The force vectors created by this type of unbalance, Figure 2, are equal in magnitude at the bearing journals, but are 180 degrees opposite in direction.

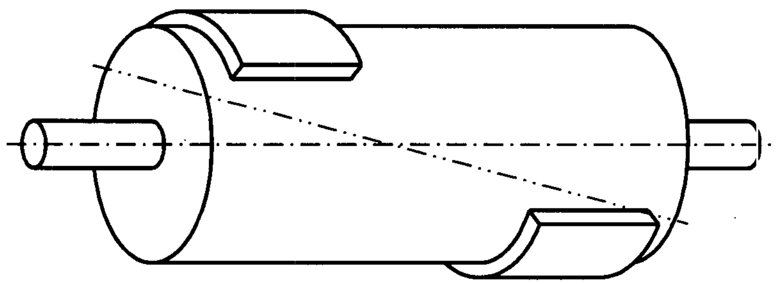


Figure 2

2.3 Dynamic Unbalance

Dynamic Unbalnce is defined as that condition where the mass axis does not coincide with the rotational axis, is not parallel to its, and does not intersect it. This condition is also known as "two plane" unbalance, Figure 3. Dynamic unbalance is always a combination of Static and Couple unbalances.

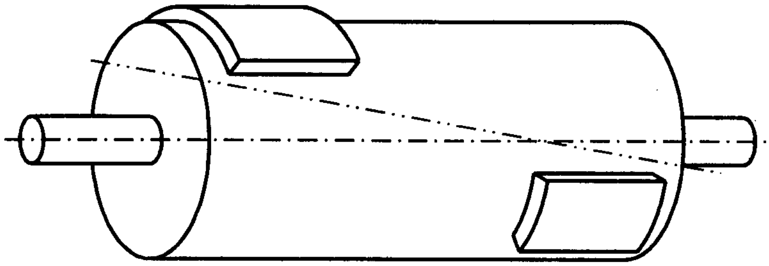


Figure 3

3. BASIC EQUATIONS IN BALANCING TECHNOLOGY

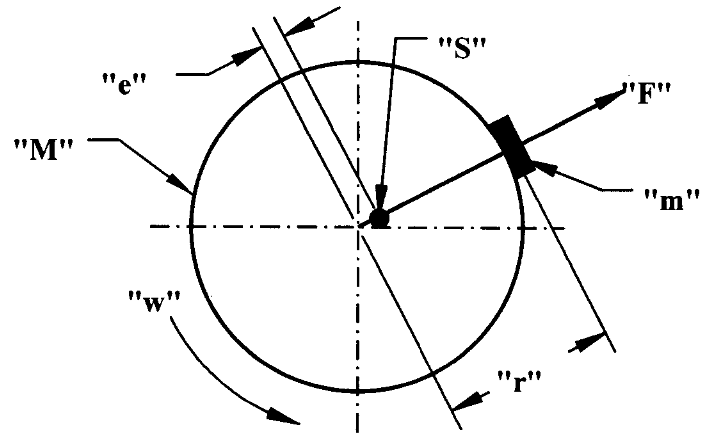


Figure 4

Figure 4 is a graphic representation of a rotor with the following characteristics:

"M"	=	Rotor Mass
"S"	=	Center of Mass
"e"	=	Displacement of Mass Center
"r"	=	Distance from center of rotor to center of unbalance mass "m"
"ω"	=	Angular Velocity
"m"	=	Unbalance Mass
"U"	=	Rotor Unbalance

3.1 Unbalance

In order to determine the unbalance "U" in the rotor, the following equations are utilized:

$$U = M \times e$$

or

$$U = m \times r$$

Unbalance is always expressed as the product of mass times distance, such as "gram-millimeters" or "ounce-inches" or "kilogram-meters".

3.2 Centrifugal Force

To determine the amount of force produced by a given unbalance, the formula:

$$F = U \times \omega^2$$

is used, where w is given as the angular velocity in radians per second. This can also be expressed as :

$$\omega = \frac{2\pi \times RPM}{60}$$

By combining these two formulas, we see that:

$$F = m \times r \times \left(\frac{2\pi \times RPM}{60}\right)^2$$

The most significant point to be determined from these formulas is that as the rotational speed of the rotor, in this case a toolholder, increased, the centrifugal force due to unbalance increases as a **SQUARE** of the speed. This fact is of primary interest as cutting speeds are continually being pushed higher, especially in the metal cutting applications. Even though a toolholder has a low initial unbalance, this unbalance may become very significant at a speed of 10,000 or 20,000 RPM.

4. Is Balancing Necessary?

Now that we are properly refreshed on balancing theory, let's focus on the problem we are here to discuss: Unbalance in Toolholders for high speed machining.

The first question is "Why do I need to balance?" The answer is "Maybe you do and maybe you don't". Please remember that we are speaking about HIGH SPEED machining - cutting at speeds of 8,000 RPM plus. Under this speed it is unlikely that you will need to balance your toolholders unless they are extremely asymmetric. At speeds of 8,000 RPM and higher however, it is easy to see from the formula for calculating centrifugal force how relatively small unbalance can produce dangerously high forces on the spindle bearings as the RPM is increased. For example, a well balanced toolholder with an unbalance of 1.0 gm-mm would produce a radial force of 0.56 pounds (0.25Kg) at 15,000 RPM. When researching toolholders and their balancing requirements, it was discovered that the average initial unbalance for CAT-50 toolholders was around 250 gm-mm. At 15,000 RPM, 250 gm-mm of unbalance produces a continuous radial force of 140 pounds (63.6 Kg)!

4.1 The Effects of Unbalance

The detrimental effects of tool and toolholder unbalance can be divided into two categories:

A. Effects on the workpiece
B. Effects on the machine

4.1.1 Effects on the workpiece

The primary result of toolholder unbalance on the workpiece is that of chatter, or ripples in the metal surface caused by the movement of the cutting tool. High frequency chatter can also result in poor surface finish. The second effect of unbalance on the workpiece is the inability to hold close tolerances, which means more scrapped parts.

4.1.2 Effects on the machine

The effects of toolholder unbalance on the milling machine are even more devastating. The centrifugal forces will cause tremendous internal stress in the spindle, normally resulting in premature spindle bearing failure. This can mean taking a million dollar machine out of production for several weeks to replace a very expensive high speed precision spindle.
Also, it has been observed that machine tools with linear way systems appear to be more susceptible to vibration created by unbalance in the toolholder and drawbar system than machines with box ways. The box ways provide excellent vibration damping due to the large surface contact area on the rails. Linear ways, while providing much lower friction and resistance to movement, do not have nearly the contact area of a box way. This tends to restrict the vibration from flowing out of the spindle into the machine bed structure where it can be properly absorbed by the massive cast iron bed. Vibration is energy, and if the energy can't get away from the spindle via the ways, then the only other path is thriugh the workpiece via the toolholder and cutting tool. This usually means chatter and loss of tool life.

4.1.3 Effects on the cutting tool

As briefly mentioned above, another negative effect of toolholder unbalance is reduced cutting tool life. Recent research by several major toolholder manufacturers has indicated that tool life can be improved by as much as 50% by using balanced toolholders!

5. Sources of Unbalance in Toolholders

Our research indicated that there are two types of unbalance sources in high speed toolholders:

- Controllable (FIXED) sources
- Uncontrollable (VARIABLE) Sources

5.1 Controllable (Fixed) Sources

FIXED SOURCES consist of such details as:

- drive slots on CAT-type toolholders
- Unground base of v-flange
- Drive Slots on HSK A,B,C,D Forms
- DIN Notch
- Any non-symmetrical geometric surface or feature

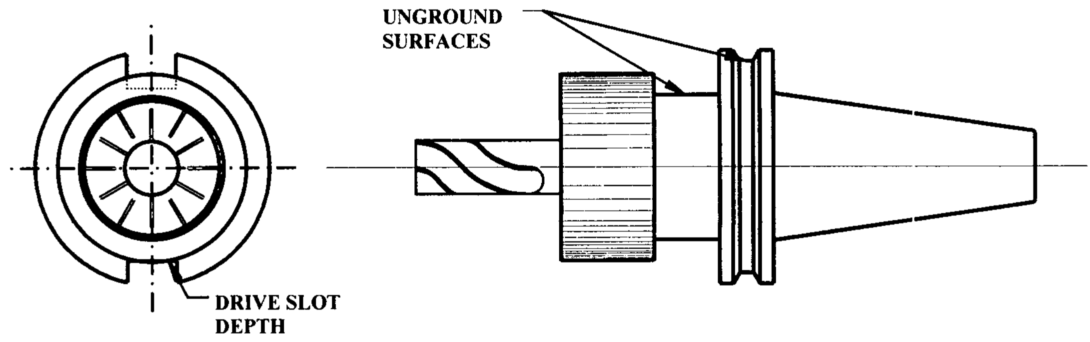


Figure 5

All of these sources of unbalance can be eliminated by either careful design or balancing of the toolholder by the manufacturer. All Toolholder used in High Speed Machining should be two-plane balanced by the toolholder manufacturer. This will insure that all of the Fixed Sources of unbalance have been removed from the toolholder.

5.2 Uncontrollable (Variable) Sources

VARIABLE SOURCES are comprised of details such as:

- Collet position - it has been detected that the collet will seat differently in the taper each time it is collapsed onto the shank of the toolholder
- Collet nut position - the radial position of the collet nut is controlled by its threads. This is a very inaccurate method and the unbalance created by the collet nut changes each time the nut is loosened and re-tightened.
- Cutting tool - in our research, we discovered that an End Mill as small as 3/8" could have enough unbalance to put a perfectly balanced Cat 40 toolholder out of tolerance for 20,000 rpm operation. The sources of tool unbalance are the Weldon flats on the tools used for set-screw type clamping, different lengths and depths on chip flutes, and of course, non-symmetric cutting tools such as a boring bar.
- Set screws used on End Mill holders
- Retention Knob

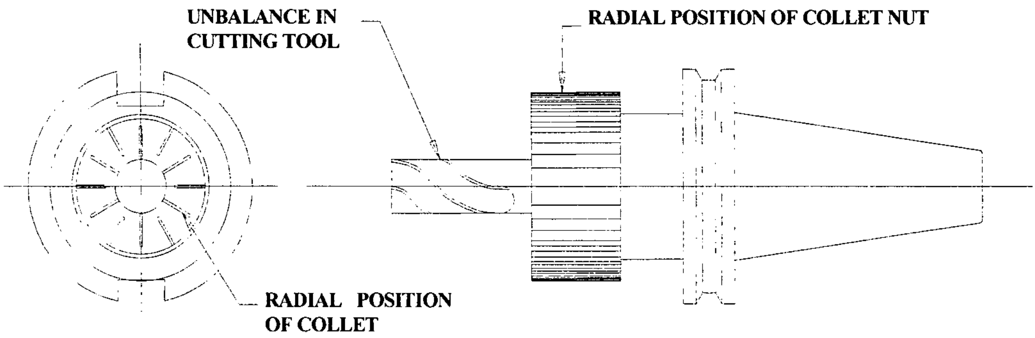
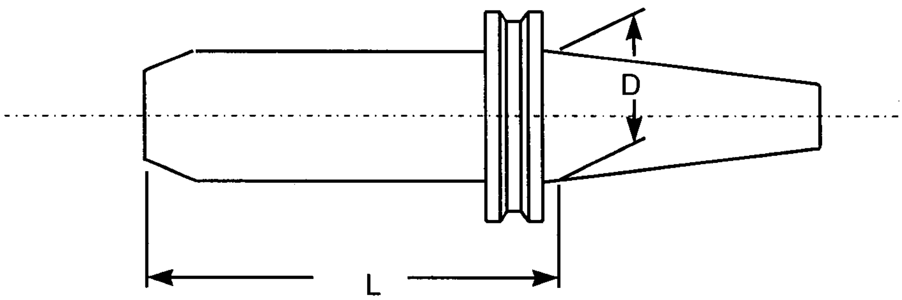


Figure 6

These sources of unbalance change every time the cutting tool is changed or the collet is loosened and re-clamped. As you can see, these sources of unbalance usually are located in one part of the toolholder - at the cutting tool end. Because they are usually centered around the cutting tool area, in most cases the Variable Sources can be eliminated with single-plane balancing. This brings us to the issue of single-plane vs. two-plane balancing on toolholders.

6. Single Plane or Two Plane?

There is one primary, fundamental question which must be addressed by toolholder manufacturers when considering the balancing of toolholders: Is the unbalance single plane (STATIC) or two plane (DYNAMIC)? If the toolholder is relatively short in length, the unbalance sources can be expected to produce a single plane unbalance. If, however the toolholder has a length which is more than two times the diameter at the gage line, then two-plane balancing may be necessary. A general guideline can be established as follows:



L>2D	1-Plane Pre-Balanced	2-Plane Pre-Balanced	2-Plane pre-balance by Toolholder Manufacturer 1-Plane Balanceable in the Field	2-Plane pre-balance by Toolholder Manufacturer 2-Plane Balanceable in the Field*	2-Plane Pre-Balanced Trim Balance in situ
L<2D	Off the Shelf	1-Plane Pre-Balanced	1-Plane Balance-able	2-Plane pre-balance by Toolholder Manufacturer 1-Plane Balanceable in the Field	2-Plane Pre-Balanced Trim Balance in situ

0 5K 10K 15K 20K 25K 30K

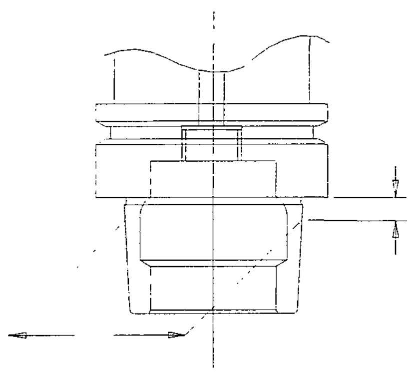
Table 1: Single Plane vs. Two Plane Balancing

This table should be used by by toolholder manufacturers as a guide for single-plane vs two-plane balancing of the toolholder to remove all of the Fixed Sources of unbalance in the main body of the toolholder. The End User, that is, the person balancing the toolholders after all components such as the cutting tool and collet have been added, will only need to single plane balance in most cases, as stated earlier.

7. HSK Toolholders

HSK toolholders have presented solutions to several problems associated with high-speed machining to manufacturers using high-speed machine tools for production. HSK toolholders utilize a clamping system that consists of many moving parts to position the toolholder in the spindle. The clamping segments exert force outward radially from inside the toolholder shank to clamp the toolholder and hold it during the machining process, and also draw the toolholder into the spindle until contact is made between the spindle face and the rear face of the toolholder flange. The taper on the HSK is nowhere near as accurate as the taper on an ANSI or ISO long taper, since the radial clamping force will deform the outside of the taper to match the spindle internal taper.

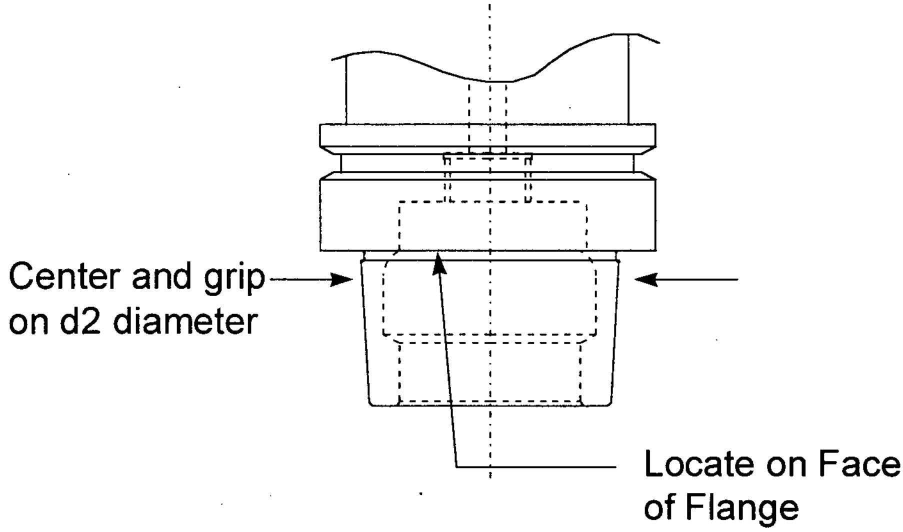
This is where the problem begins for balancing HSK toolholders. In order to balance a toolholder for high-speed operation, it must be accurately located and held in the balancing machine. Due to the complexity and the number of moving parts in the HSK drawbar and clamping system, it is not possible to get a repeatable unbalance reading when the part is unclamped, removed from the balancing machine, then placed back on the machine and reclamped. The unbalance tolerance, for example, on an HSK 63A toolholder operating at 24,000 RPM would be 0.9 gm-mm. On a 985 gram toolholder, this is equal to a displacement ("e" in figure 4) in the center of gravity of the toolholder of 0.000039" (0.001 mm). In order to maintain this unbalance reading in the balancing machine if the part is unclamped and re-clamped, ALL of the drawbar and clamping components would have to re-position themselves to within a few millionths on an inch! Our testing has indicated that this does not happen in the HSK drawbar system.



TYPICAL HSK TOOLHOLDER

7.1 The Hofmann HSK System

Albert Einstien once said: "Everything should be as simple as possible. But not simpler." This is the guidline which was used for our HSK adapter system. It has no moving parts to influence the unbalance and give false unbalance readings like a drawbar system does. What it does do is use the diameter d2 and the flange face to locate the toolholder in the fixture for balancing. The adapter "grips" the toolholder on the d2 diameter tightly to allow the unbalance to be measured, using a set of precision machined spring fingers. Here's how it works:



Using this adaption method, we have successfully balanced HSK toolholders from size 40A up to and including size 125A. Plus, when you take the toolholder out of the adapter and the place it back in, the adapter will re-position the toolholder in the balancer to within 0.5 microns, which results in excellent repeatability in the balancing machine.

8. Pre-Balanced vs Balanceable

8.1 Pre-Balanced

All Toolholders used for high-speed machining should be two-plane pre-balanced by the toolholder manufacturer. In many cases, as reference earlier in Table 1, this is more than adequate for the spindle speed and operation being performed. Once again, the purpose of this balancing operation is to remove the FIXED Sources of unbalance in the toolholder. But because we also have to deal with the VARIABLE Sources of unbalance, there are several types of toolholders which cannot be pre-balanced by the very nature of their design.

- Shrinker – By the very nature of its design, the Shrinker is the best design available in toolholders for balance considerations: it has no moving parts, and once it is pre-balanced it does not lose its balanced state. The only VARIABLE source of unbalance in the Shrinker is the cutting tool unbalance, which may or may not require compensation depending on spindle speed and cutting tool size.

- Hydraulic Chucks – Hydraulic chucks are another excellent toolholder from a balancing standpoint. There is only one moving part in a hydraulic chuck, which is the Actuating Screw. But since the Actuating Screw is located radially by a positive stop, it always conmes back to the same position when changing the cutting tool. Like the Shrinker, the only VARIABLE source of unbalance is the cutting tool.

- Collet Chucks – With Collet Chucks, the situation is not the same. As pointed out earlier, every time the collet nut is loosened to change the cutting tool and then re-tightened, its radial position – and, therefore, the unbalance – changes. Collet chucks can only be pre-balanced for operation below 10,000 RPM. Above this speed, the tool and toolholder assembly need to be re-balanced after changing the cutting tool. The body of the toolholder, minus the collet and collet nut, should be pre-balanced, but the changing unbalance condition requires that a "Balanceable" feature be added to this type of toolholder for high speed operation.

- End Mill Holders – The primary VARIABLE Source of unbalance in an End Mill Holder is the large Set Screw which holds the cutting tool. Because of its large size, this Set Screw can cause fluctuations of 50 – 70 gm-mm just by changing cutting tools. This comes from the Weldon Flat which must be present on the cutting tool for use with this type of holder. On a ¾" End Mill, the tolerance on the radial location of the Weldon Flat is +/- 0.020" (0.5 mm), which means the radial position of the locking Set Screw can vary up to 0.040" (1.0 mm) from one tool to another! As with a Collet Chuck, the body of the toolholder should be two-plane pre-balanced, but even then there is no easy answer as to where to position the locking Set Screw radially when performing this pre-balance operation.

- Milling Chucks – By the very nature of their design, Milling Chucks have a HUGE amount of VARIABLE Source unbalance. The nut on a Milling Chuck weighs almost as much as the rest of the toolholder, and this nut moves dramatically in its radial position every time the cutting tool is changed. Because of this, Milling Chucks cannot be pre-balanced in any way. They must be balanced after all components have been added.

8.2 Balanceable Toolholders

The Fixed Sources of unbalance can be easily removed from the toolholder by drilling or grinding to remove material and balance the toolholder body. This is done by the toolholder manufacturer as a part of the toolholder manufacturing process. The Variable Sources, however, can only be removed after the tool and toolholder are in their final condition, ready to go into the Milling Machine. It should be clear that drilling or grinding on the toolholder to remove Variable Sources of unbalance is not a good idea, because after a few tool changes the toolholder would be destroyed!

Several Toolholder Manufacturers have developed systems for balancing their toolholders to remove the Variable Sources of unbalance after the tool and toolholder are in their final condition.

- **Axial Tapped Holes**

  Lyndex Corporation has created a balancing system for toolholders which consists of 8 to 12 tapped holes which are AXIALLY positioned in the toolholder. These tapped holes are used to add set screws and other small balance weights such as balls or rods to offset the unbalance in the toolholder.

- **Radial Tapped Holes**

  Tooling Innovations, the creator of the heat shrink toolholder known as the "Shrinker", untilizes a system where they drill and tap several equally spaced holes radially into the toolholder. The tapped holes are usually a #6-32 or #8-32 thread size and the toolholder can be balanced by adding set screws to balance or by placing a set screw into each hole and balancing by changing the radius of the set screws. The screws can be held in place by a non-cementing type of Loctite or by using a Nylok type of set screw.

- **Balancing Rings**

  Two toolholder manufacturers, Kennametal and Iscar/ETM, have developed systems which use two rotating rings which are integrated into the body of the toolholder. Both rings have an equal unbalance. Initially, the two rings are placed with their unbalance mass 180 degrees opposite of each other, in effect canceling each other out. Then the tool and toolholder are placed into the balancing machine and the unbalance is determined. Now the rings can be adjusted until they produce a force vector equal and opposite to the unbalance vector, thus creating a balanced toolholder.

- **Boring Bars**

For boring bars, one company utilizes a system with a built in micrometer which is used to set the cutting tool on the boring bar. As the cutting tool is advanced outward radially, an internal counterweight moves off-center in the opposite direction, keeping the tool in balance at all radial settings.

Needless to say, as high speed machining gains in popularity and demand, other methods of balancing tools and toolholders will become available on the marketplace.

9. Balance Tolerance

The final point which must be addressed in this discussion is that of balance quality, or how low of an unbalance is acceptable. The answer to this question is readily available in the ANSI Standard for Balance Quality of Rotating Rigid Bodies, ANSI S2.19-1975 or in the Iso Standard 1940. The purpose of these standards is to make recommendations concerning the balance quality of rotating rigid bodies, particularly as it relates to the permissible residual unbalance as a function of the maximum service speed of a particular rotor. One of the functions of the ANSI standards is to assign balance quality "grades" to different related groups of rotors, based on experience which was gained with rotors of various types, sizes, and service speeds.

By definition, the balance quality grade "G" is equal to the product of the specific unbalance, "e" times the rotational speed "ω" or:

$$G = e \times \omega$$

The units for balance quality "G" are millimeters per second.

As we have seen earlier, "e" can also be defined as the unbalance "U" divided by the rotor mass "M" or:

$$e = \frac{U}{M}$$

where "U" is in gram·millimeters and "M" is in grams.

By substitution, we see that:

$$G = \frac{U \times \omega}{M} \quad \text{or}$$

$$G = \frac{U}{M}\left(\frac{2 \times \pi \times RPM}{60}\right)$$

By solving for U, we obtain:

$$U = \frac{9.54 \times M \times G}{RPM}$$

By utilizing the balance quality tables in the ANSI standards, it is shown that the balance quality for machine tool drives is **G 2.5**, and the balance quality for grinding machine drives is **G 1.0**. It can be logically determined that the goal for toolholder balancing should fall somewhere in between these two limits, since it would serve no practical purpose to balance below the level of vibration present in the spindle.

9.1 Example:

From the formula above we can quickly calculate the balance tolerance , "U", for a given weight toolholder operating at a known RPM. For example, the tolerance for a 3 kg tool and toolholder operating at 25,000 RPM is:

$$U\ (upper) = \frac{9.5 \times 3000\ grams \times 2.5\ mm/sec}{25{,}000}$$

U (upper) = 2.85 gram-millimeters

and

$$U\ (lower) = \frac{9.5 \times 3000\ grams \times 1.0\ mm/sec}{25{,}000}$$

U (lower) = 1.14 gram-millimeters

Therefore, it is determined that the balance tolerance for this toolholder is between 1.14 and 2.85 gram-millimeters.

9.2 A Word About G 2.5

Having stated that G 2.5 should be the unbalance tolerance for toolholders used in high speed machining, I would like to point out that there are limits to this system. As the toolholder weight gets lower and the spindle speed goes above 30,000 RPM, a G 2.5 requirement starts to generate unbalance tolerance values that are not achievable on "standard" commercially available balancing machines used in a normal shop environment. The cutoff point on the tolerance should be 1 gm-mm. Unbalance values below this are so miniscule that they can change just by varying the temperature in the shop more than a few degrees.

9.3 Unbalance Tolerance And Cutting Force

It is my opinion that a much more logical approach to unbalance tolerancing for toolholders is to base the balance tolerance on the cutting force of the operation being performed. For example, if the operation being performed is machining aluminum to remove large volumes of material with a roughing end mill, the cutting forces could easily reach 200 pounds (90.9 Kg). It is not logical or cost effective to balance the toolholder to G 2.5 in this case, because surface finish is not an issue and the cutting force will be an order of magnitude higher than the centrifugal force created by the unbalance. On the other hand, if the operation is a die / mold application where a small ball nosed end mill is being used for machining a mold in Rockwell 50C, then unbalance will be critical. Experience has shown us that in this case, with light chip loads and small cutting forces, proper balance will help to yield a great surface finish and eliminate any post-machining operations such as polishing, buffing, or de-burring.

In the following example, I have arbitrarily selected that the centrifugal force due to unbalance should be 5% of the cutting force. Using this parameter, consider the following example:

For the roughing operation, we will use the following parameters:

Tool:	BT-50
Tool Weight:	6 pounds (2.7 Kg)
RPM:	15,000
Cutting Force:	200 pounds (90.9 Kg)
Unbalance Force:	10 pounds (4.5 Kg)
Balance Tolerance:	20 gm-mm
G 2.5:	4.3 gm-mm

As you can see, 5% of 200 pounds of cutting force is 10 pounds. The unbalance that will produce 10 pounds of force at 15,000 RPM is 20 gm-mm. G 2.5 would require a balance tolerance of 4.3 gm-mm, which would give no additional benefit for the time spent to balance from 20 gm-mm down to 4.3 gm-mm.

On the other hand, for the die / mold operation we see the following:

Tool:	BT-30
Tool Weight:	0.75 pounds (0.34 Kg)
RPM:	22,000
Cutting Force:	20 pounds (9.17 Kg)
Unbalance Force:	1 pound (0.45 Kg)
Balance Tolerance:	1 gm-mm
G 2.5:	0.3 gm-mm

Here we see very little difference between the tolerance calculated using 5% of the cutting force and the G 2.5 tolerance. Using this method, when the unbalance tolerance needs to be low because of the operation being performed, it is important, .but if the process doesn't require a tight unbalance tolerance, then time is not wasted chasing a very low, sometimes unachievable number.

10. Conclusion

In summarizing, we can present the following points:

- As speeds on machine tools are increased, centrifugal force from unbalance becomes a damaging factor.
- Balancing can improve the performance of high speed (8,000 RPM +) machining.
- There are three types of Unbalance: Single Plane, Couple, Two Plane.
- Each type of unbalance may apply to Toolholder Balancing under the right conditions.
- The tool, toolholder, and retention knob should be balanced as an assembly.
- Unbalance in Toolholders comes from two sources: Fixed and Variable.
- Toolholders used in high speed machining should be two-plane balanced by the manufacturer to remove the FIXED Sources of unbalance.
- Most VARIABLE Sources of unbalance can be removed by single plane balancing.
- HSK Toolholders can be accurately balanced using special fixtures.
- Some toolholders can be pre-balanced, others must be balanced after assembly using a balanceable feature
- The balance tolerance for a given toolholder may be easily calculated using the ANSI and ISO Standards, but the Balance Tolerance should be based on the process being performed, not just a blanket rule of G 2.5 regardless of the application.