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A DISCUSSION OF THE MECHANICAL LIMITATIONS OF MACHINERY USED FOR SAMPLE-PREPARATION PROCESSES

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INTRODUCTION

Many semiconductor failure analysis sample-preparation procedures require mechanical machining processes. These processes include removing encapsulant, removing heat spreaders, cutting of the sample for cross sectioning, package substrate printed circuit board delayering, die thinning by grinding and polishing, die delayering, and many others. The machines used for mechanical sample preparation have ultimate limitations based on the machine's accuracy, resolution, repeatability, and environmental effects. These limitations can/may affect the results of the sample-preparation process. Limitations to ultimate performance include the intrinsic machine resolution, accuracy, and repeatability of the tool-positioning system as well as tolerance limitations resulting from the tool bits, pads, and other consumable components. Note that a *tool,* as used here, is an end mill, a grinding tool, a saw blade, or other simple functional device. A *machine,* or machine tool, is what utilizes a tool to perform a specific task. A milling machine is a machine. The end mill it uses is a tool.

A BRIEF DISCUSSION OF TERMS

The dictionary definition of *accuracy* is "the extent to which a given measurement agrees with the standard value for that measurement."[1]

The standard used as the "standard value" generally is a National Institute of Standards and Technology (NIST) traceable length standard with an absolute tolerance defined by the reference standard and class. A length reference is normally a gauge block. A gauge block is a piece of metal having flat and parallel opposing gauge surfaces (Fig. 1). A grade 2 NIST 100 mm gauge block matches the NIST reference standard to +0.0003/−0.00015 mm, but only at the standard conditions:[2]

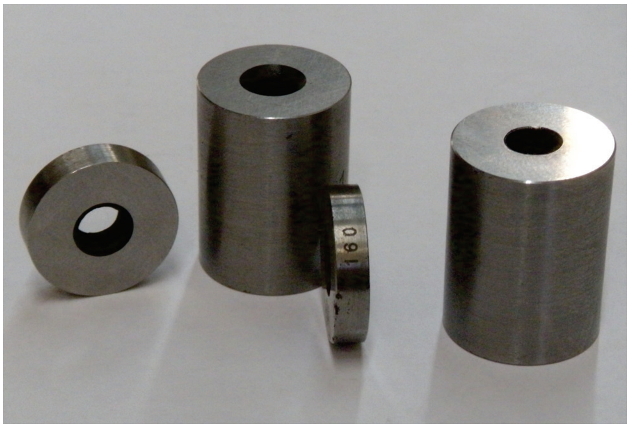
Fig. 1 **Representative cylindrical gauge blocks**

- Temperature = 20 °C (68 °F)
- Barometric pressure = 101,325 Pa (1 atm)
- Water vapor pressure = 1333 Pa (10 mm of mercury)
- CO_2 content of air = 0.03%

The steel of the gauge block expands with increasing temperature at a rate of 11.5 ppm/°C.[2] A 1° increase in temperature of the 100 mm gauge block will result in a dimensional change of 0.00115 mm, or nearly three times its specified accuracy.

The dictionary definition for *resolution* is "the fineness of detail that can be distinguished."[3] When taking any measurements, there is a limiting fineness of the measurement, as determined by the measurement reference. When using a ruler marked with only 1 mm increments, a length can only be determined to the nearest 1 mm. If the ruler's overall length is off by 10%, the measurement can still be taken to a 1 mm resolution. Resolution is not a function of accuracy.

The definition of *repeatability* is "the variation in measurements taken by a single person or instrument on the same item and under the same conditions."[4]

The easiest way to illustrate the difference between accuracy and repeatability is to refer to the rifle target in Fig. 2. A tight grouping is repeatability.

In addition to these terms, the geometric properties of parallelism and orthogonality determine the performance of a mechanical system.

Simple mechanical devices used for sample preparation, such as diamond saws, dimplers, and many others, have easy-to-understand mechanical systems, and as long as they are properly maintained and calibrated, they will perform their designated tasks. With simpler machines, if the quality of the results is lacking, then service and adjustment are required.

A more complex machine is the flat lapper. There are two basic types of lappers: open face, where the sample being lapped is mounted to a fixture that is placed inside or attached to a rotating ring, and lappers with a mast that supports a sample holder and provides sample rotation and movement across the lap surface. Either type can use abrasive lapping films or a slurry feed system. Critical parameters on a lapper include axial runout, lap flatness, and the parallelism of the rotational, scan, and lap spindle axes. The axial runout is the variation in height of the lap surface at the edge as the lap rotates. For controllable results with any lapper, the lap should be flat and not have axial runout. The parallelism of the rotational, scan, and lap spindle axes determines the surface shape of the sample. Axial runout will produce scalloping at the sample edges. Lack of parallelism of the rotational axis will produce a conical surface. Lack of parallelism of the scan axis will produce a spherical surface. Aligning all three axes is difficult to impossible, depending on the machine, but it is necessary if die delayering is to be done. A 1 or 2 µm axial runout on the lap, or the rotational axis not being parallel to the spindle, or the scan axis not being in line will produce a nonplanar result. The geometries of the inaccuracies are easy to calculate. A 0.02 mrad misalignment of the sample holder rotational axis will produce a 10 mm^2 sample with the corners more than 100 nm lower than the center. When delayering, this conical shape can make the results unacceptable. Accuracy depends on set-up adjustments for the machine. Ongoing successful sample preparation depends on maintaining these adjustments. Periodic adjustments may need to be performed by a specially trained technician or engineer.

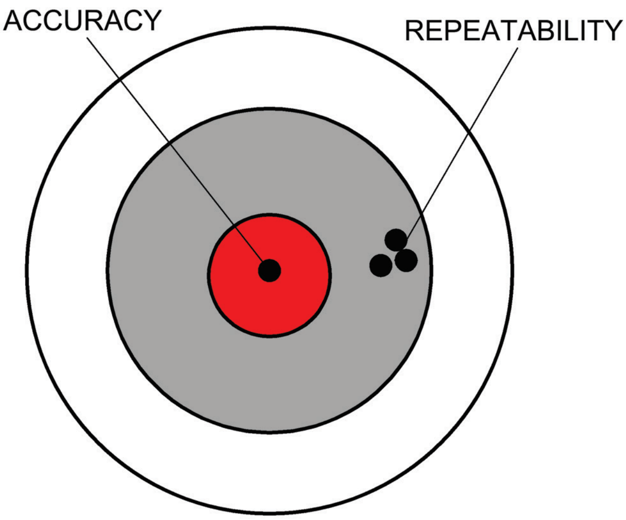

Fig. 2 **Accuracy as opposed to repeatability**

> **"IN LINEAR POSITIONING SYSTEMS, SUCH AS USED ON THESE MACHINES, THE LINEAR MOTION IS COMMONLY PRODUCED WITH A LEAD SCREW, AND THE POSITION IS MEASURED BY A LINEAR ENCODER AND SCALE."**

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THREE-AXIS-MOVEMENT MACHINES

There are machines available for die thinning or delayering that have movement in three axes as well as a rotating spindle that holds the tool. It is with these machines that the concepts of accuracy, resolution, and repeatability are most relevant. These machines move a tool over the die surface by moving the sample in the *X* and *Y* axes and moving the tool in the *Z* axis.

In linear positioning systems, such as used on these machines, the linear motion is commonly produced with a lead screw, and the position is measured by a linear encoder and scale. A computer controls the motor driving the lead screw so that the encoder gives the desired position value. The encoder has specifications for linearity and resolution and, occasionally, zero reference repeatability. In a numerically controlled machine, there is always a reference or zero point that is periodically checked to establish a positional reference. This is almost always at the extreme travel of the machine in *X* or *Y*, while most work is done near the center of the travel. The temperature effects on the linear encoder scale then alter all positional values by a function of the total travel from the zero point. This means that the longer the travel, the greater the zero shift produced by temperature changes. A machine with 200 mm of travel will have twice the thermal zero shift as a machine with 100 mm of travel.

In addition to the temperature effects, there is a tolerance on the zero position. This is a result of the switches used to detect when an axis is at the zero position. These switches may be mechanical, optical, or magnetic. No matter which type of switch is used, it will have some level of uncertainty that results in uncertainty in the zero position.

The resolution of the machine is a function of how well the scale can be measured by the linear encoder. A good encoder can provide positional resolution of 50 nm, but the accuracy is a function of the scale.[5] A typical optical scale will have a nonlinearity of 0.005 mm per meter of travel and a thermal expansion coefficient (T_c) of the material to which it is mounted.[5] Steel has a T_c of 11.5 ppm/°C, and the T_c for aluminum is 23 ppm/°C. A 100-mm-long scale will change 0.0023 mm/°C. All of this is additive. The uncertainty due to scale resolution adds to the nonlinearity, zero position uncertainty, and the thermal variations of the scale. With a typical ±2° variation in temperature and a 100-mm-long scale, zero uncertainty of ±0.5 μm, and the scale nonlinearity, the positional uncertainty is ±5.6 μm. This is 110 times greater than the encoder resolution.

THE CONCEPT OF UNCERTAINTY

Uncertainty is the ultimate tolerance on any positional move. The factors that affect uncertainty are repeatability, accuracy, geometric factors, interaction between the axes of movement, and environmental effects. The repeatability, as shown in Fig. 2, will drift in position resulting from temperature effects, and the pattern center will move as a result of the other factors. Repeatability will always be less than uncertainty.

THE GEOMETRY OF MACHINE PERFORMANCE

All machines involve linear and rotational movement. Most machines involve multiple-axis movements. The geometric relationship of the axes to each other will directly affect the position in the other axes as movement takes place. If the *X* and *Y* axes are at 89° instead of 90°, a move in either axis will produce a positional shift of 1.745% of the move in the other axis. Resolution, accuracy, and repeatability in one axis are meaningless if the axes are not truly orthogonal. If the *Z* axis is not normal to the *X-Y* plane, changes in *Z* position produce changes in the tool tip's position referenced to the *X-Y* plane.

Determining axis uncertainty requires knowing the geometric relationships of all three axes and the rotational axis of the tool. This requires the manufacturer to specify the orthogonality of the axes to each other and the normality of the *Z* axis and spindle to the *X-Y* plane (Fig. 3). Although the geometric variables do not directly affect the repeatability, the interaction in position from geometric inaccuracies makes each axis's real position a function of the other axes' positions.

In addition to the geometric problems, the runout of each axis also must be considered. The linear bearings or linear positioner used in each axis have runout in the perpendicular axes. A typical precision-grade profile linear bearing will have 2 μm runout in the vertical and horizontal axes.[6] That is, as the linear bearing is moved, it can move a small amount vertically and horizontally. Even super-precision bearings have a runout of 1.5 μm. The runout in one axis adds directly to the positional uncertainty of the other two axes. The runout also produces rotation about each axis as a function of the separation between the bearings used. As an example, Fig. 4 shows a single axis using four linear bearings on two profile rails in a square pattern:

- A 2 μm horizontal and vertical runout in *X* will produce ±2 μm movement in the *Y* and *Z* axes.
- The rotation possible is a result of +2 μm on one bearing and −2 μm on another. The pitch is then a function of the bearing spacing. The yaw becomes a function of the rail spacing.
- The pitch and yaw affect true position in all three axes according to the geometric relationships and the distance from the sample to the axis plane.

All of these variables directly add to other sources of positional uncertainty. Vertical runout on the *X* axis bearings adds directly to the uncertainty of the *Z* axis

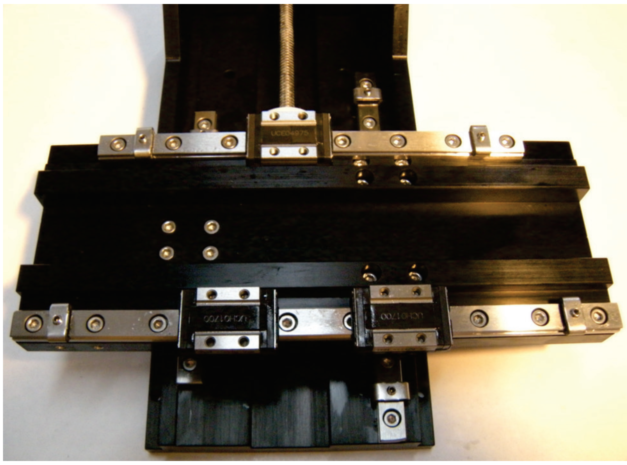

Fig. 3 Typical *X-Y* movement mechanism with the *X* axis stage removed. There are three bearings instead of four on each axis, although the runout and orthogonality effects are the same as in the text.

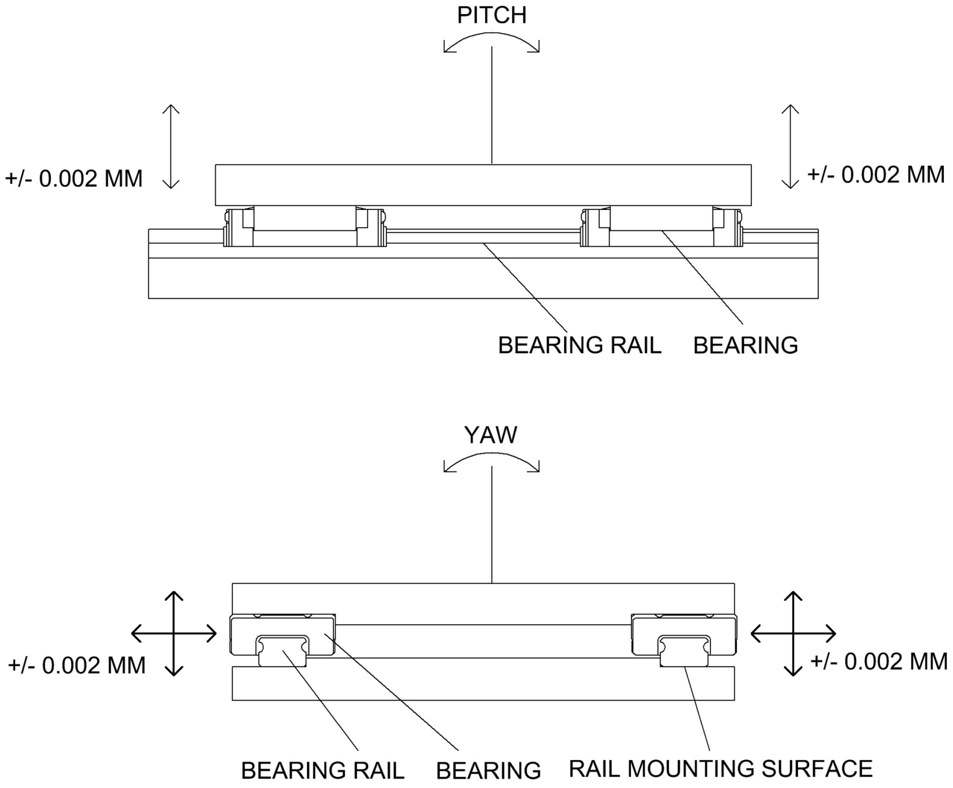

Fig. 4 **Linear bearing arrangement and the effects of runout**

position, and the horizontal runout adds directly to the *Y* axis uncertainty.

PROCESSES FOR BACKSIDE THINNING

Backside thinning of a sample often requires the removal of encapsulant, die-attach pad, and die-attach adhesive. These processes are usually defined by the position of the extreme edge of the cutting tool. As the tool is rotating, the eccentricity of the tool and spindle and the actual tool diameter all determine the location of the extreme cutting edge. A typical end mill will have a diameter tolerance of ±13 µm[7] or more. A very good spindle and collet for securing the end mill to the spindle may have a runout of ±7.6 µm.[8] The runout is a function of the concentricity of the spindle to the collet axes. The end mill may also have runout that results from the cutting edges not being coaxial with the shank. All of this makes the uncertainty of the edges of the machined area ±20 to 25 µm from tool and spindle tolerances alone. A desire to define the machined area to ±1 µm requires that the running tool and spindle inaccuracies be taken into account. This can only be done in situ. That is, an operator must adjust the machined area during machining. Once this is done, the repeatability of the *X-Y* movement only needs to be within the desired positional tolerances to produce an acceptable result.

Adjusting tool position and travel during operation is problematic. Attempts to have video viewing during operation are often obscured by slurry and swarf. Because the video camera cannot view directly down the tool axis, there must be some parallax. The parallax makes any *Z*-positional movement also appear to be a movement in the *X-Y* plane. Moving the sample to a viewing position creates measurement and correlation problems.

When thinning a die to a measured surface contour, *X*- and *Y*-positional uncertainties have an effect on the *Z* position due to the surface profile. The maximum slope of the profile, multiplied by the *X-Y*-positional uncertainty, adds to the *Z* axis positional uncertainty when determining the overall profile reproduction uncertainty. A slope of 20 µm/mm will add to the *Z* axis uncertainty as the *X-Y*-positional uncertainty (in mm) times the 20 µm/mm slope. Therefore, a ±5 µm *X-Y* uncertainty will introduce an additional *Z* axis uncertainty of 0.1 µm.

WHAT IS REQUIRED

The system repeatability must be equal to or slightly less than the desired positional accuracy. If a machined pattern must be maintained at ±1 µm, then the repeatability of *X-Y* positioning must be 1 µm or less. A resolution of less than one-half of the positional uncertainty is unnecessary and only increases the cost of the system. The *Z* axis uncertainty must be equal to or better than the required profile integrity. If it is desired to reproduce a surface profile to ±1 μm, the Z axis repeatability need not be less than 0.5 μm. If *X-Y*-positional repeatability is not constrained directly, it can be defined as the maximum profile slope divided by the *Z* axis maximum uncertainty. Therefore, if a 1 μm *Z* axis limit is required, and the maximum profile slope is 20 μm/mm, the *X-Y* uncertainty needs only to be less than 50 μm. Nowhere is there a requirement for 50 nm resolution in any axis or "submicron" accuracy.

If a machine is required to thin plastic-packaged devices and produce a thinned die with less than ±5 μm in thickness variation, the following specifications are all that are required. Tighter specifications only result in increased purchase and maintenance costs:

- *X* and *Y* axis resolution: 1.0 μm
- *Z* axis resolution: 0.5 μm
- *X, Y* axis independent repeatability: 2.0 μm
- *Z* axis independent repeatability: 1.0 μm
- Spindle runout: 10 μm
- Axis orthogonality: 0.05 mrad, maximum
- Variation from straight line travel: 0.003 mm per 25 mm of travel, including runout
- Axis pitch and yaw: 0.05 mrad, maximum
- Stage deflection: 50 Newtons/μm, maximum

The axis resolution defines the minimum required scale resolution. It should be 50% or less of the repeatability. The spindle runout limits the effective increase in tool diameter caused by "wobble." The axis orthogonality and axis pitch and yaw each limit axis-to-axis interaction to 0.05 μm per millimeter of travel. Because all materials and machines are elastic, the stage deflection specification is required to limit the *Z* axis positional change as a result of the tool forces.

In total, over a 25 mm^2 area, the *X-Y*-positional uncertainty is approximately 15 μm with 2 μm repeatability. The *Z*-positional uncertainty is approximately 11 μm with repeatability of less than 2 μm. Any more than this is unnecessary and costly, and any less does not guarantee performance.

The axis positional uncertainty comes into play if the surface profile is measured by different equipment. If this is done, all of the positional uncertainties of both the measuring system and the processing machine add. Because the positional uncertainty is much greater than repeatability, the integrity of profile reproduction comes into question.

FRONTSIDE DELAYERING REQUIREMENTS

Delayering requirements are much more complex. Delayering on a flat lap requires that the device rotational axis and the scan axis be parallel to the platen rotational axis to a degree of precision that is not normally encountered. Maintaining 10 nm planarity of a 10 mm^2 die sample requires that all axes be within 0.002 mrad. In addition, the vertical runout of the platen must be less than 0.2 μm. Measuring the runout is problematic, as are the alignment measurements, but all are possible with the right measurement equipment and personnel. Delayering on a backside thinning machine is even more problematic because axis alignment is either not available or difficult to adjust to the accuracy required. Delayering requires that the spindle be orthogonal to the *X-Y* plane within 0.0067 mrad for a 3-mm-diameter tool. A larger tool diameter tightens the requirements. Normally, the spindle orthogonality of a backside system is more than 10 times that required to do die delayering. Additionally, 10 nm *Z* axis repeatability is not truly available. This indicates that using a flat lap is difficult and using a backside thinning system is not realistically possible. If one is delayering a 5 μm design-rules die, almost anything can be used. Currently for the latest design rules, only a very carefully set up flat lap can meet the requirements.

CONCLUSIONS

Claiming or stating resolution as accuracy is disingenuous because accuracy is a function of many different parameters. Accuracy, repeatability, and resolution must be matched to the process requirements. Increasing resolution, repeatability, and accuracy beyond what is required will not increase sample quality. The desired process results should determine the equipment specifications. There are some critical parameters that currently are not specified by some equipment suppliers, such as the geometric relationships and straight line movement variations of each of the axes. To ensure that the desired results are obtained, these parameters must be defined. For some processes, there are no readily available, simple, and easy equipment solutions…yet.

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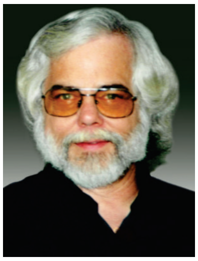
ABOUT THE AUTHORS



Kirk Martin has 40 years of experience in designing and building specialized equipment for all aspects of the semiconductor industry, from crystal growth through final test and failure analysis. In 2005, he became a founder of RKD Engineering, which designs and builds equipment for semiconductor failure analysis and sample preparation. Kirk has patents in the fields of sample preparation, chemical vapor generation, and electrostatic discharge detection and mitigation.

Nancy Weavers has 30 years of experience in applications in the semiconductor and test equipment industries. She started at National Semiconductor in 1982. In 2006, she became the Chief Executive Officer of Left Coast Instruments, a semiconductor test equipment and electron microscope imaging sales and marketing company. She sits on the Board of Advisors for the San Joaquin Delta Electron Microscopy Program. Previously, she was a Vice President at Nisene Technology Group.

NOTEWORTHY NEWS

ANADEF WORKSHOP

The 15th ANADEF Workshop will be held **June 7 to 10, 2016,** at Belambra Business Club, Seignosse-Hossegor (Landes), France. The conference addresses new issues related to the latest technological developments in electronic component failure analysis, presented through tutorials, plenary sessions, micro-workshops, as well as participation by equipment manufacturers and suppliers.

ANADEF, a French nonprofit scientific society established in 2001, meets biennially to bring together industry experts and mechanism scientists concerned with the prevention, detection, and failure analysis of electronic components and assemblies. For more information, visit anadef.org.