

Ballbar testing in tandem with circle, diamond, square machining tests.

Introduction

This whitepaper describes how Renishaw ballbar tests can be used in tandem (or in some cases in lieu of) a “Circle diamond square” cutting test to evaluate machine tool performance. Firstly it gives an overview of the circle diamond square contouring test and the measurements used to assess machine performance. It then describes the Renishaw ballbar system and the results provided by the automatic plot diagnosis software. This is followed by detailed information about how the ballbar diagnosis results can be used in advance of cutting tests to provide a valuable insight into machine performance before any metal is cut, thereby saving both time and cost.

Circle diamond square machine tests

Cutting tests have always provided a popular method of assessing machine tool performance. The machine is used to manufacture a test piece under controlled conditions. The machine’s performance is then evaluated by checking the dimensional accuracy of the test piece on a CMM (Co-ordinate measuring machine).

In 1966 the Aerospace Industries Association of America defined a series of standardised cutting tests for CNC milling machines in National Aerospace Standard NAS979¹ (*Uniform cutting tests – NAS series - Metal cutting equipment specifications*).

Section 4.3.3.5.1 of this standard defines a composite cutting test involving machining of circular, diamond and square shaped profiles under CNC control. This test became known as the “circle, diamond, square test”.

NAS979 is now deemed “Inactive for design after 31 May 2013” with no direct replacement. However, similar circle, diamond, square tests are now defined in both International Standard ISO 10791-7 2014² and American Standard ASME B5.54 2005³.

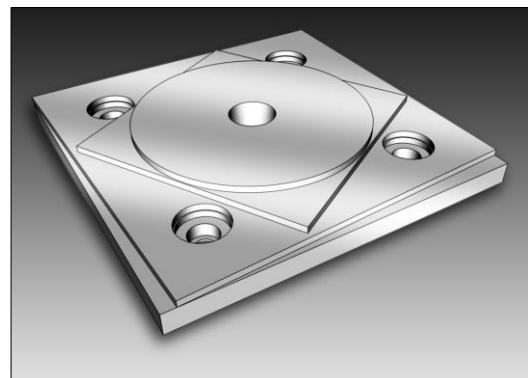


Figure 1 – ISO 10791-7 320 mm test piece

ISO 10791-7 defines a “positioning and contouring test” which uses a test piece with circle, diamond and square shaped features which are similar (but NOT identical) to those in NAS979. It defines three sizes of test piece to cater for a range of machine sizes, designated M1_80 (80 x 80 mm), M1_160 (160 x 160 mm) and M1_320 (320 x 320 mm), together with target tolerances for each. Figure 1 shows a schematic of the 320 x 320 mm test piece.

Section 8.2 of ASME B5.54 defines a “precision contouring test” using slightly modified versions of the 160 and 320 mm test pieces contained in ISO 10791-7, with differing inspection procedures and without any specific tolerance limits (tolerances are to be agreed between supplier and customer).

This whitepaper focuses on the 320 mm test piece defined ISO 10791-7, but the underlying principles are generally applicable.

Figure 2 shows the key dimensions of the 320 mm ISO 10791-7 test piece.

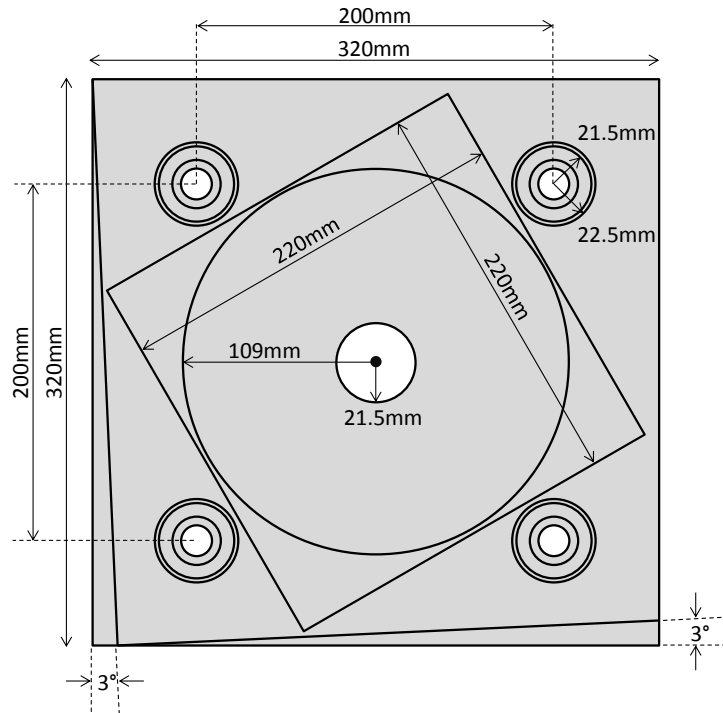


Figure 2 - M1_320 test part key dimensions

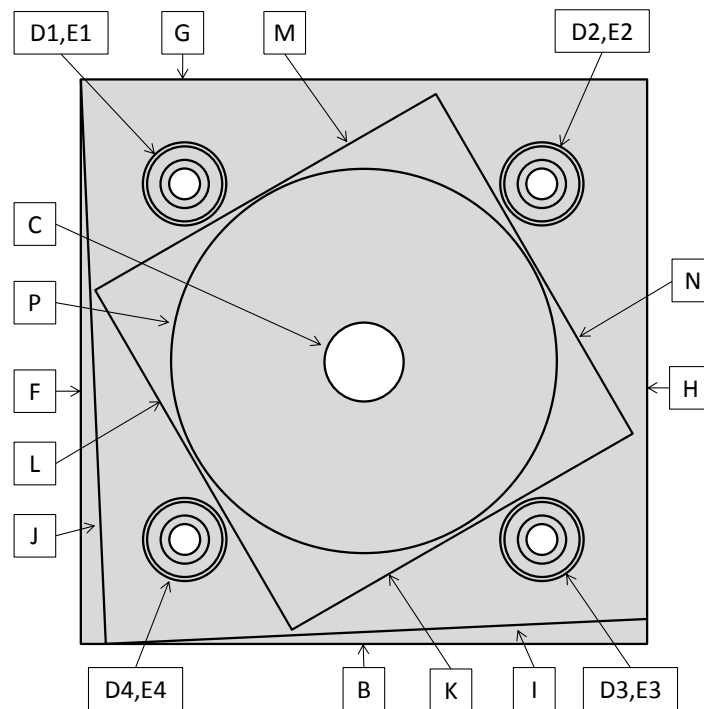


Figure 3 - M1_320 test piece - feature nomenclature

Figure 3 names the key features. The flat top surface of the diamond is datum face A. Face B and hole C are also datum features. The deepest counter-bored holes in the corners are for fixturing.

The bored holes (E) are approached in the positive direction of the X & Y axes, the counter-bored holes (D) are approached in the negative direction. Datum surface B is parallel to one of the machines linear axes (X or Y).

ISO 10791-7 defines 31 target tolerances between machined features A thru P. These are listed in the table below, for the 320 mm test piece.

No	Feature	Tolerance	Limit (mm)	
1	Central Hole	Cylindricity of hole C	0.015	
2		Perpendicularity between Hole C axis and datum plane A	0.015	
3	Square	Straightness of side B	0.015	
4		Straightness of side F		
5		Straightness of side G		
6		Straightness of side H		
7		Perpendicularity of side H to datum plane B	0.020	
8		Perpendicularity of side F to datum plane B		
9		Parallelism of Side G to datum plane B	0.020	
10		Diamond	Straightness of side K	0.015
11			Straightness of side L	
12	Straightness of side M			
13	Straightness of side N			
14	Angularity of 30° angle of side K to datum plane B		0.020	
15	Angularity of 60° angle of side L to datum plane B			
16	Angularity of 30° angle of side M to datum plane B			
17	Angularity of 60° angle of side N to datum plane B			
18	Circle	Roundness of circle P	0.020	
19		Concentricity of external circle P to datum hole C	0.025	
20	Sloping faces	Straightness of face I	0.015	
21		Straightness of face J		
22		Angularity of 3° of side I to datum plane B	0.020	
23		Angularity of 93° of side J to datum plane B		
24	Bored holes	Position of D1 with respect to datum hole C	0.050	
25		Position of D2 with respect to datum hole C		
26		Position of D3 with respect to datum hole C		
27		Position of D4 with respect to datum hole C		
28		Concentricity of holes E1 to D1	0.020	
29		Concentricity of holes E2 to D2		
30		Concentricity of holes E3 to D3		
31		Concentricity of holes E4 to D4		

Table 1 - Tolerances for machined features of 320 mm test piece

After machining, the test piece is taken for measurement on a CMM. If the target tolerances are not met, the machine may need adjusting, and the test repeating. The whole process can therefore be rather expensive and time consuming. Not only is there the cost of the material blanks, there's also the machining and measurement time. This may be compounded significantly if CMM facilities are not available nearby, adding extra transportation costs and delays.

Nevertheless, physical machining tests still provide a very practical demonstration of the accuracy of the parts a machine can produce. This is why an updated version of the circle diamond square test has been included in the current International and American standards ISO 10791-7 and ASME B5.54.

Ballbar testing

The use of a telescoping ballbar for machine tool testing arose from work by the highly respected metrologist James Bryan at Lawrence Livermore National Laboratory in the USA. This work resulted in a US patent⁴ being granted in 1984 for a 'Telescoping Magnetic Ball Bar Test Gage'.

A telescoping ballbar consists of a telescopic bar with magnetic ball and socket joints on each end and a displacement sensor inside. One ball joint is placed on the machine table, and the other in the machine spindle, with the telescopic bar in between. The machine is then programmed to interpolate a circular arc around the table mounted ball joint whilst the sensor records the deviations of the machine spindle from the programmed path (see Figure 4). The “circularity” of the resulting error trace provides a simple numeric result indicating the machine’s contouring performance. If the machine is tested using both CW and CCW arcs, then analysis of the recorded data can provide a detailed insight into the machine’s performance and the source of any errors.



Figure 4 - Renishaw QC20-W ballbar

Such is the value of the ballbar test, it has been included in numerous National and International Standards, including ISO 230-4⁵, ASME B5.54^{6,7}, ASME B5.57⁸, JIS B-6190⁹, GB/T17421.4¹⁰, dating back to 1992.

Renishaw introduced their first “Quick-check” ballbar testing system in 1992, quickly followed by the QC10 ballbar system in 1994. Since then the product has been regularly updated. The QC20-W ballbar system, available today, includes wireless operation, a comprehensive range of accessories and software, and extensive foreign language support.

The key to the popularity of the Renishaw ballbar is the speed of the test, combined with the detailed machine performance diagnosis it can provide.

Ballbar plot analysis and error diagnosis

The main result from the ballbar test is the circularity* of the plot. The recorded data is centred and the difference between the maximum and minimum radii is computed. In ISO 230-4 and B5.54 standards, this result is called the “circular deviation”. See Figure 5.

**Note: Ballbar plot circularity is calculated in the same way as the roundness or circularity of the machined circle in the circle diamond square test.*

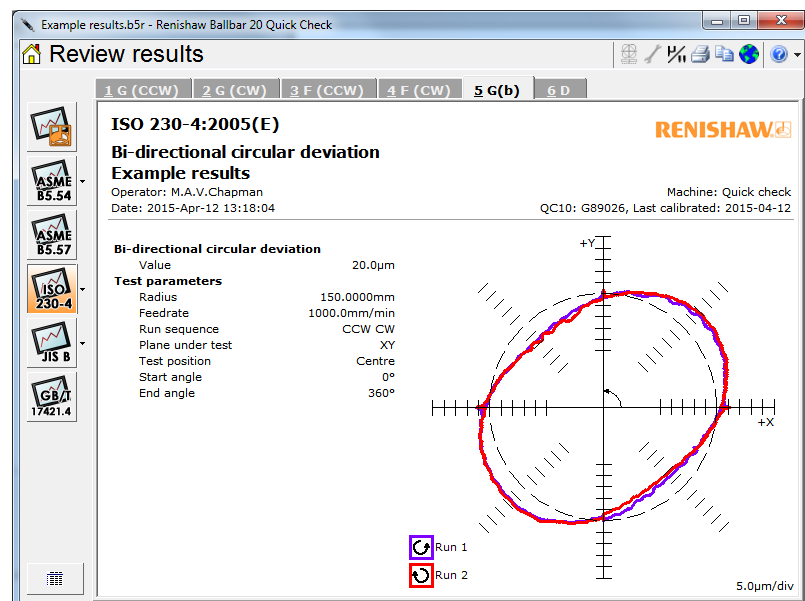


Figure 5 - Renishaw analysis in accordance with ISO230-4

However, the simple calculation of plot circularity only utilises a tiny fraction of the information contained within the ballbar data. Detailed inspection of the plot shape can indicate what types of errors are present in the machine being tested. The traces in Figure 6 show how different errors in the machine distort the ballbar plot shapes from a 150 mm radius bidirectional ballbar test at a feedrate of 3,000 mm/min in the XY plane. Where CW and CCW traces are different, the CW data is shown in blue and CCW data in red. A plot scale of 5 μ m/division is used throughout.

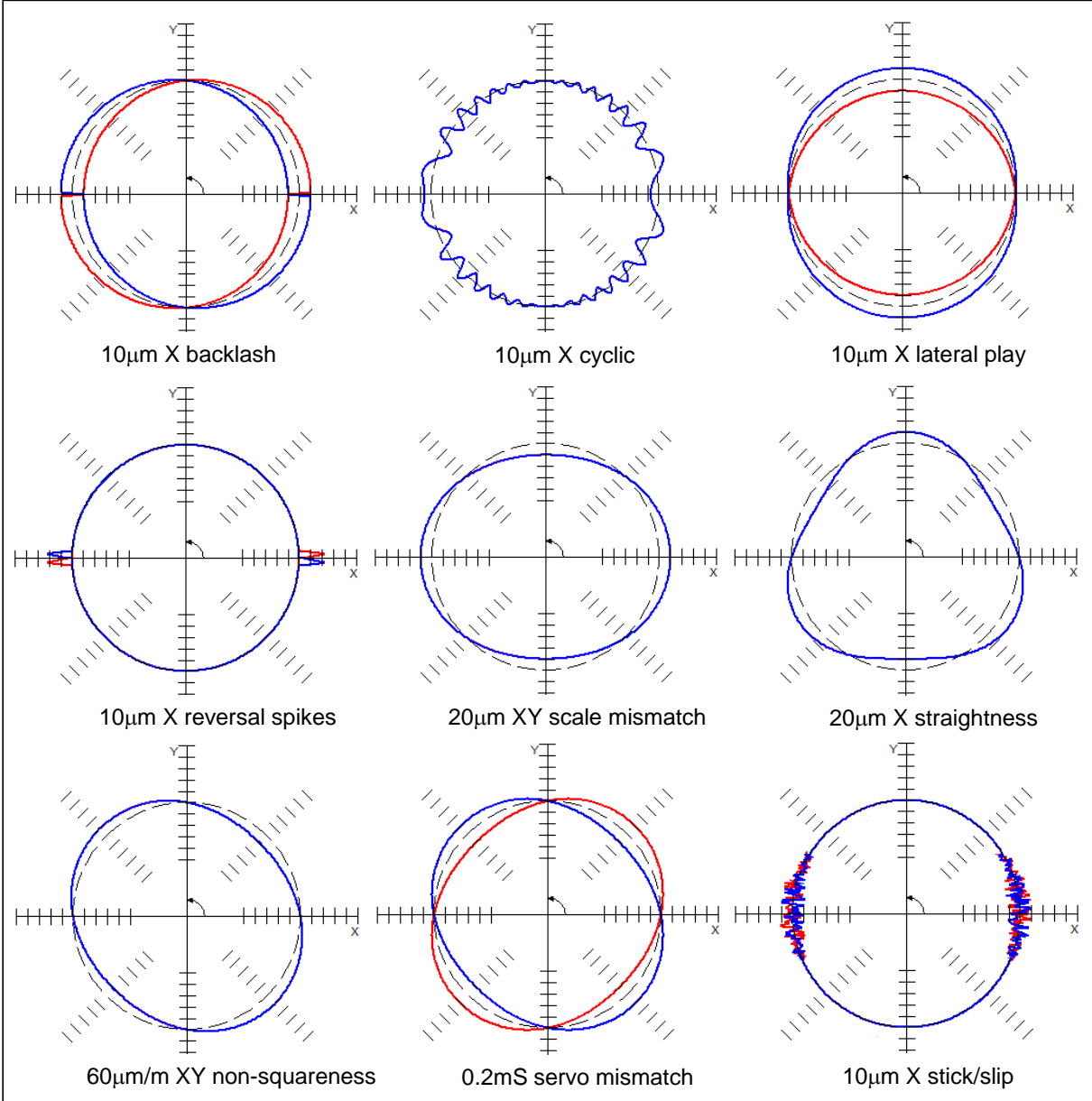


Figure 6 - Ballbar plot distortion from a variety of machine errors

If a machine contains only one or two errors it may be possible to visually inspect the plot to determine the source of those errors. However, in many cases, machines contain numerous superimposed errors, making visual identification of the error sources very difficult, if not impossible.

Figure 7 shows an example plot from a simulated machine with a combination of errors in both X and Y axes. Identification of the individual machine errors by visual inspection of this plot is very difficult. To overcome this problem Renishaw's ballbar software includes advanced mathematical algorithms that can diagnose which machine errors are present, and quantify the amount of each of them.

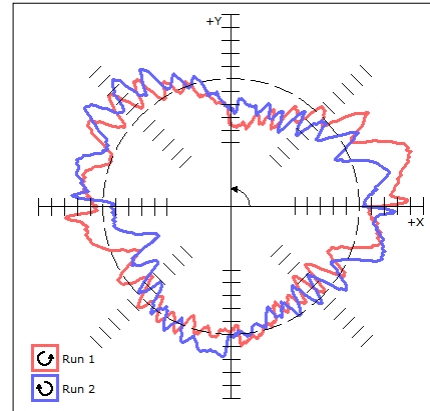


Figure 7 - Complex error plot

Figure 8 shows the results of using Renishaw's ballbar error diagnosis software on the set of data shown in Figure 7. The raw data is shown by the red and blue traces which have been overlaid with thin black traces showing the fitted diagnosis. The numeric values on the left indicate the amount of each machine error that has been identified.

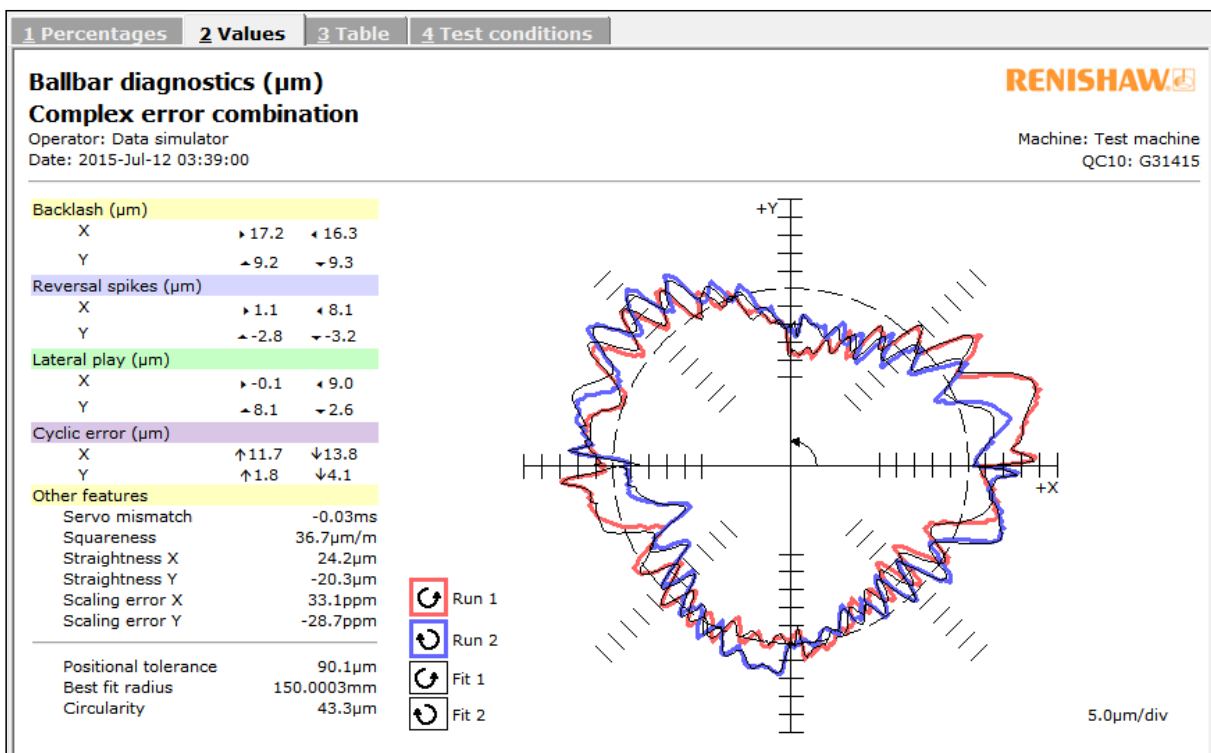


Figure 8 - Ballbar error diagnosis results ("Values" tab)

If the ballbar length has been calibrated using the ballbar calibrator (see Figure 9) the diagnosis is able to identify individual scaling errors in X and Y axes (rather than just the mismatch between them) and also to estimate the positional tolerance the machine can achieve within the test area.



Figure 9 - Ballbar calibrator

Renishaw's ballbar software can also present the diagnosed results in a different format by ranking the error sources in order of their percentage contribution to the circular deviation result and listing the most significant contributors first, as shown in Figure 10 .

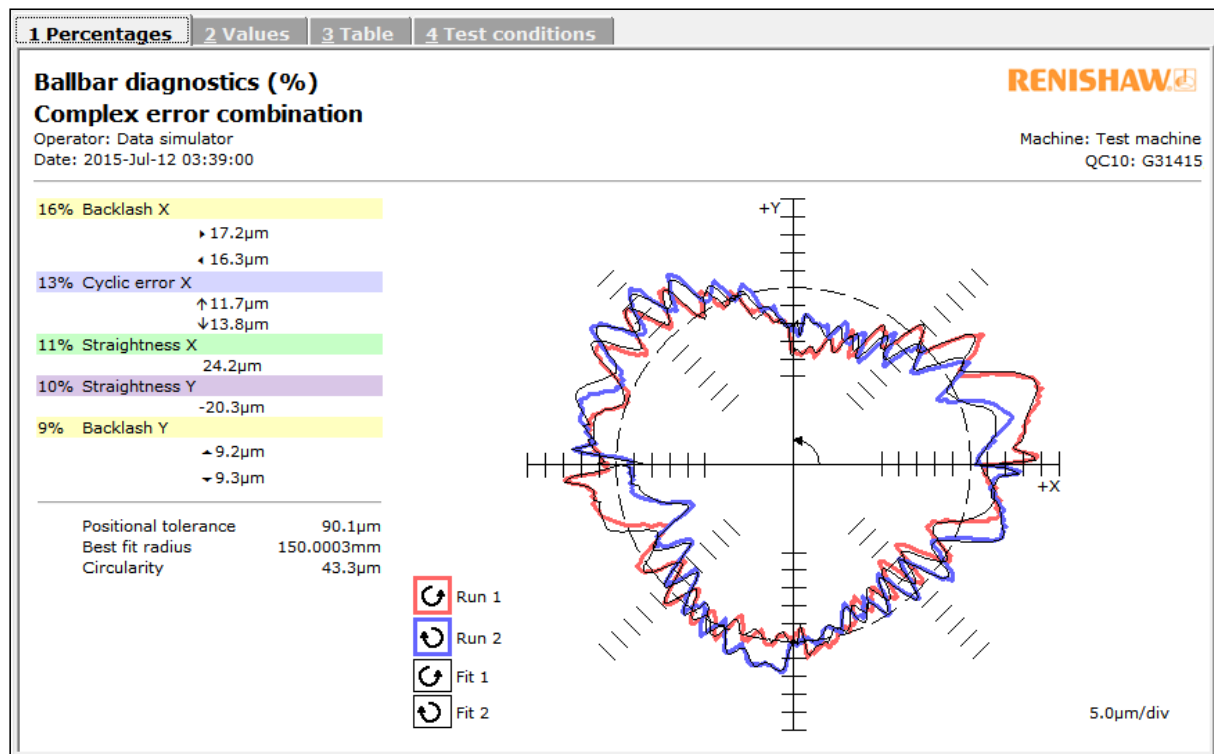


Figure 10 - Ballbar diagnosis results ("Percentages" tab)

In this example, the diagnosis shows that the dominant contributor to the non-circularity (circular deviation) of the plot is the backlash error in the X axis.

A ballbar test takes only a few minutes to complete, and the diagnostic results are available immediately. Ballbar testing can therefore provide an extremely quick and powerful way of assessing a machine's performance and identifying areas where remedial action may be required.

It can also provide a valuable insight into the results that might be obtained from the circle, diamond, square test, before any metal is cut, saving valuable time and money.

Advanced ballbar test setup

When carrying out ballbar tests as a precursor to circle, diamond, square machining tests, the ballbar should be set-up as follows;

- **Ballbar test radius.** Ideally the test radius should be chosen so that the test circle is of a similar size to the circle, diamond, square test piece. Renishaw's standard ballbar kit supports test radii of 100, 150, 250, 300, 400, 450, 550 and 600 mm. The ballbar calibrator supports 100, 150 and 300 mm. The optional small circle adaptor kit supports radii of 50 mm and includes a 50 mm ballbar calibrator. Subject to these constraints, and the ISO 10791-7 test piece sizes, it is suggested that the ballbar test radii shown in Figure 11 are used.

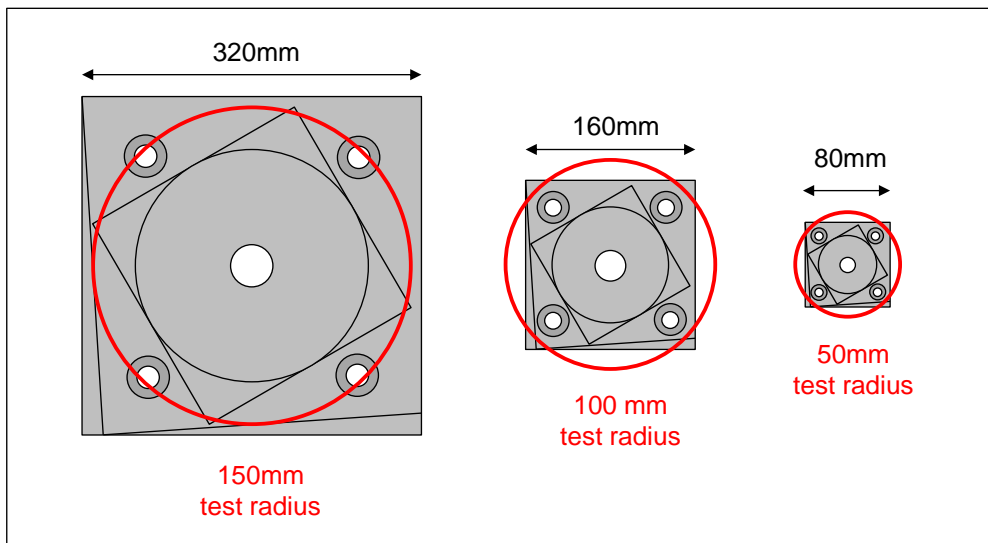


Figure 11 - Suggested test radii for 80, 160 and 320 mm ISO 10791-7 test pieces

- **Ballbar length calibration.** Ideally the ballbar length should be calibrated before the test starts, using the ballbar calibrator. This ensures that the analysis results will then include a positional tolerance result. It is also good practice to enter the expansion coefficient of the test piece material and its likely temperature into the ballbar software, so that material expansion compensation is also performed.

Note: If machining an ISO 10791-7 test piece with a target position tolerance of 0.050 mm for holes D1,2,3 & 4, then material expansion compensation is not critical. So, if you are uncertain about the expansion coefficient and temperature, enter an expansion coefficient of 0.0 ppm/°C and a material temperature of 20°C.

- **Test location** - The ballbar test should be centred at the same location that the test piece will be located.
- **Test Feedrate** - The feedrate for the ballbar test should be the same as that used for the finishing cuts during the machining test.
- **Test arc** - Select a test arc of 360° with some overshoot (suggest 90° or 180° to simplify programming). This will ensure reliable capture of axis reversal features.
- **Test runs** - Carry out 2 runs, one CW and the other CCW. This will ensure that complete ballbar diagnostic results are available.

Ballbar data analysis

Once ballbar data has been captured it should be analysed using the ballbar machine error diagnosis software. By comparing plot circularity, diagnosed machine errors, and positional tolerance results (see Figure 8) with the target tolerances for the circle, diamond, square test piece (see Table 1), it is possible to anticipate* potential problems with the cutting test.

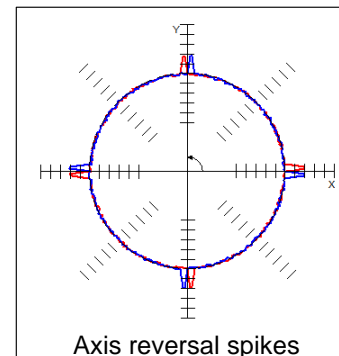
**A note of caution is required here. A cutting test will include additional sources of error such as spindle deflection, vibration, tool change non-repeatability, etc. which are not included in the ballbar test. The geometry and sizes of the tests are also different. A direct correlation of results is therefore not possible. However, if the machine produces ballbar results that indicate the target tolerances*

required on the machined test piece will not be met, it is recommended that remedial action is undertaken.

The results of the ballbar test may be compared with the target cutting test tolerances as follows;

- **Roundness of machined circle.** If the ballbar test result shows a circularity error which is greater than the target roundness tolerance of circle P in ISO 10791-7 (or the target circularity tolerance of the contoured circle L in ASME B5.54) then it is possible that the machined circle will be out of tolerance.

- Use the “Percentages” diagnosis tab (See Figure 10) to determine the dominant causes of the ballbar test circularity error and take remedial action accordingly.
- *Note, if the dominant cause of the ballbar circularity error is large outward axis reversal spikes, the machined circle may not be seriously affected. This is because these spikes may be smoothed out by the blending effect of the cutter radius. (Although there is likely to be a visible blemish in the surface finish).*



- **Positional tolerance of the four corner holes.** Compare the ballbar positional tolerance result (see Figure 8 - “Values” diagnostic tab) with the target positional tolerance required on the four corner holes. If the ballbar result is more than double* the target positional tolerance value, then it is possible that the position of one or more of the four bored holes will be out of tolerance.

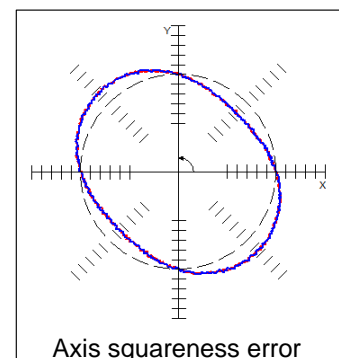
- Use the “Percentages” diagnosis tab (see Figure 10) to determine the dominant error sources and take remedial action accordingly.

**Note. The ballbar positional tolerance provides an estimate of the positional tolerance that will be achieved between 2 features anywhere within the test circle. Whereas ISO 10791-7 and ASME B5.54 target tolerances are defined relative to the central hole, which halves the feature separation and the effect of many machine errors.*

- **Angular accuracy of machined faces.** Compare the ballbar squareness diagnosis result (see Figure 8 - “Values” diagnostic tab) with the target angular tolerances for the machined diamond, square and 93° faces. This will require conversion of the “indicated runout” tolerances in ISO 10791-7 into angles in $\mu\text{m}/\text{m}$ or arcseconds, to match the ballbar diagnosis.

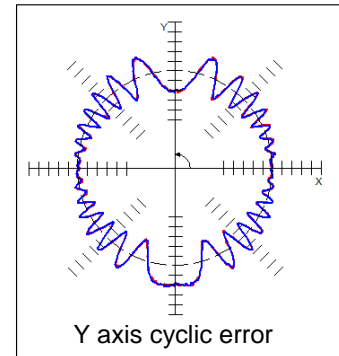
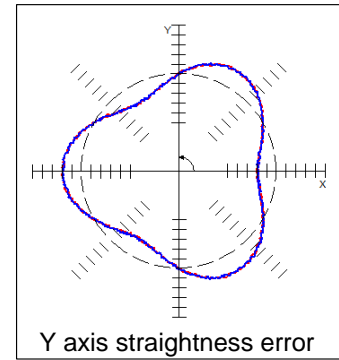
For example, consider the 0.02 mm perpendicularity tolerance for side H to datum plane B for the 320 mm ISO test piece. Side H is 320 mm long. So a tolerance of 0.02 mm over a 320 mm length is equivalent to an angular deviation of $0.02/320 = 62.5 \mu\text{radians} \approx 13 \text{ arcseconds}$.

- If the diagnosed squareness error from the ballbar test exceeds the target angular tolerances then it is likely that the angles of the machined faces will be out of tolerance. The squareness of the machine may need adjusting or compensating.



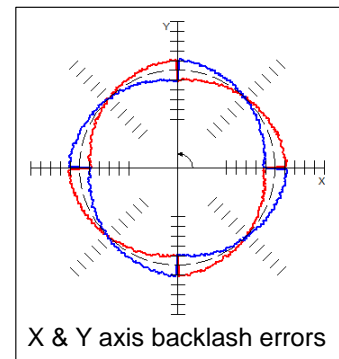
- **Straightness of machined faces.** Compare the ballbar straightness results (“Values” diagnostic tab) with the target straightness tolerances for the machined diamond, square and 3° and 93° faces.

- If the diagnosed straightness error from the ballbar test exceeds the target straightness tolerances then it is likely that the machined faces will be out of tolerance. Axis guideway straightness may need adjusting or compensating.
- If the diagnosed axis cyclic error from the ballbar test exceeds the target straightness tolerance of the diamond faces then there is a possibility that this will cause a problem with the straightness of these machined faces. Note - cyclic errors will not affect the straightnesses of the faces of the square, and are very unlikely to affect the 3° and 93° degree faces.



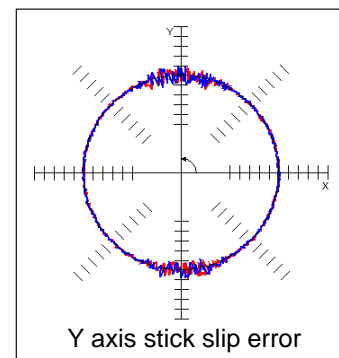
- **Concentricity of counter-bores in corner holes.** ISO 10791-7 and B5.54 both specify that the bore location must be approached in the opposite direction to the counter-bore location. It is therefore instructive to compare the diagnosed values for lateral play and backlash for the X and Y axes (See Figure 8 - “Values” diagnostic tab) with the concentricity tolerance required on the four corner bores and counter-bores.

- If the diagnosed backlash or play errors from the ballbar test exceed the target concentricity tolerance then it is likely that the concentricity of these holes will be out of specification. The axis backlash may need adjusting or compensating and/or guideway play adjusting.



- **Surface finish of circle and 3° and 93° faces.** When machining the 3° and 93° faces, one axis moves at almost the programmed feedrate, whilst the other moves at approximately 1/20th of that feedrate. If there is a problem with the axis lubrication or clearances, the slow moving axis may exhibit stick-slip motion causing problems with the surface finish (or even, in extreme cases, the straightness) of the 3° or 93° machined faces. Surface finish problems may also appear around the axis reversal areas of the machined circle.

- If the ballbar trace shows excessive noise around any of the axis reversal points indicating the presence of stick-slip motion in one of the axes then the axis guideway lubrication or clearances may need adjusting.



The above section indicates how the ballbar test can be used to check for potential problems with the machine, in advance of any cutting tests. Once any problems have been resolved, cutting tests can be performed, if required, with increased confidence levels.

Benefits of using a ballbar test

- Potential problems can be identified before metal is cut, saving time and cost.
- If problems are identified, ballbar diagnostic software can highlight areas of the machine that may require attention.
- Ballbar tests can also be used to test large machines where a suitably sized test piece would be impractical. (With additional extension bars the QC20-W ballbar can be used for test radii up to 1350 mm).
- Ballbar tests are so quick that they can be repeated at regular intervals to build up a machine performance history. This allows trends to be identified and maintenance scheduled before problems reach a critical level. Figure 12 illustrates one of the machine history plots that are available in Renishaw's ballbar software. The software allows graphs versus time of any diagnosed feature, e.g. circularity, squareness, backlash etc.

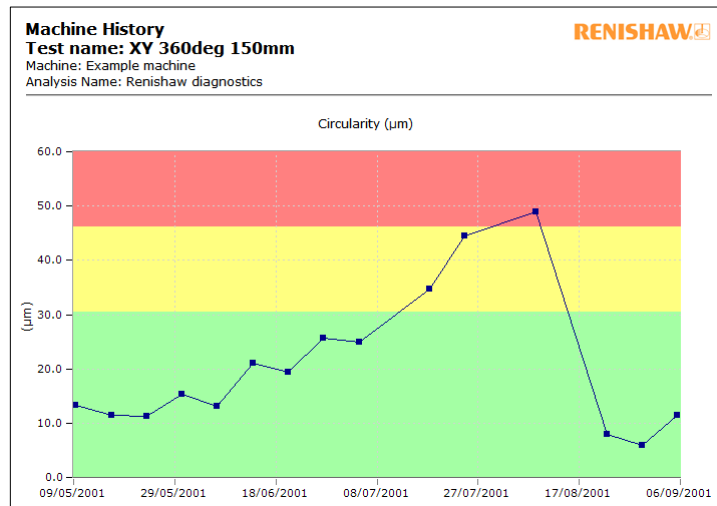


Figure 12 - Machine history plot

Benefits of cutting tests

Cutting tests are sensitive to additional sources of error that ballbar tests cannot detect, for example:-

- Spindle problems (alignment, vibration, worn bearings etc.)
- Machine deflection due to cutting loads
- Additional surface finish problems due to tool chatter and coolant problems etc.
- Tool change repeatability problems (B5.54 requires a tool change before each bore and counter-bore of the four corner holes are machined).

Conclusion

This whitepaper has given an overview of the circle, diamond, square machining test and the measurements it uses to assess machine performance. It has described how the Renishaw ballbar system and diagnosis software can be used in advance of metal cutting tests to provide detailed insights into the machine performance, before any metal is cut, saving both time and cost.

Once initial machine performance has been benchmarked, ballbar tests can also be used on an ongoing basis to monitor changes in machine performance and identify trends, allowing maintenance to be scheduled before problems arise.

Footnote 1 - ASME B5.54 recommendations

It is worth noting the sound advice given in Appendix A3¹¹ of ASME B5.54 which recommends a minimum test set for quickly estimating the performance of a three axis machine tool as follows;

A3.1 Contouring performance tests using circular tests in 3 planes using, for example, a telescoping ballbar.

A3.2 Linear positioning accuracy and repeatability test of each axis, using, for example, a laser interferometer.

A3.3 Diagonal displacement tests along 4 body diagonals using a laser interferometer.

A3.4 Precision contouring machining tests including, for example, the classic “circle diamond square” test.

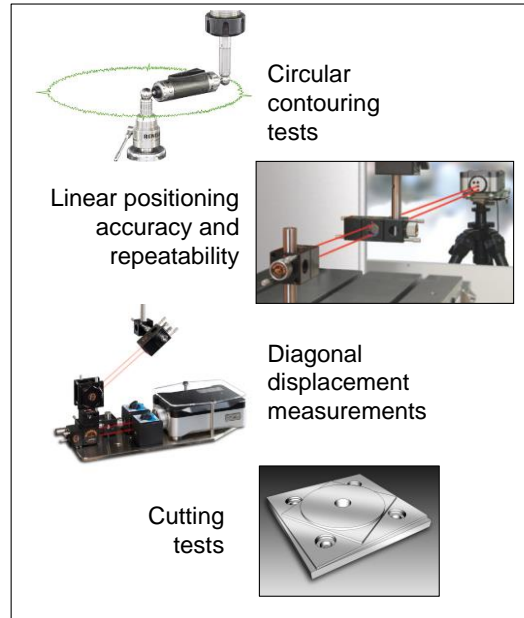


Figure 13 - B5.54 recommended test set

Footnote 2 - The frustum cutting test

NAS979, B5.54 and ISO 10791-7 standards also describe a cone frustum cutting test for 5 axis machines. This test involves moving all 5 axes simultaneously to machine an angled conical section test piece, as illustrated schematically on the left in Figure 14.

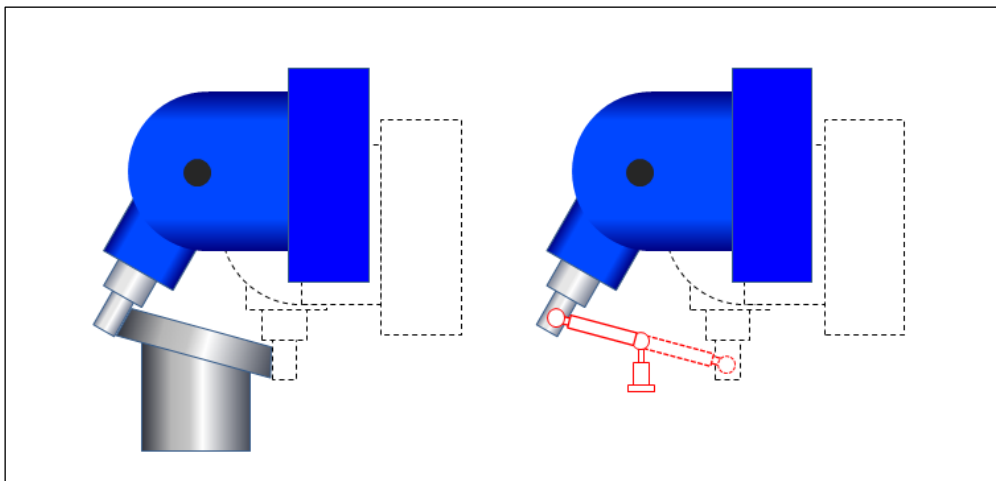


Figure 14 - Frustum cutting test for 5 axis machines

It is possible to use a ballbar to assess the circularity of frustum that the machine is likely to achieve by using the ballbar setup shown on the right in Figure 14. The ballbar analysis software will correctly calculate the circularity, but the machine error diagnosis will require careful interpretation since it is only designed to diagnose problems from 3 axis machine tests.

References

1. National Aerospace Standard NAS979 (*Uniform Cutting Tests - NAS series - Metal cutting equipment specifications*). Section 4.3.3.5.1 - Composite cutting test.
2. International Standard ISO 10791-7 2014: Test conditions for machining centres - Part 7: Accuracy of finished test pieces.
3. American Standard B5.54-2005 Methods for Performance Evaluation of Computer Numerically Controlled Machining Centres. Section 8.2 Precision contouring test.
4. US Patent No US4435905 A - Telescoping magnetic ball bar test gage - James B. Bryan
5. International Standard ISO230-4:2005 - Test code for machine tools - Part 4: Circular tests for numerically controlled machine tools.
6. American Standard B5.54-1992 Methods for Performance Evaluation of Computer Numerically Controlled Machining Centres. Section 5.9.3 Contouring Performance Using Telescoping Ball Bars.
7. American Standard B5.54-2005 Methods for Performance Evaluation of Computer Numerically Controlled Machining Centres. Section 7.11 Contouring Performance Using Telescoping Circular Tests.
8. American Standard B5.57-2012 Methods for Performance Evaluation of Computer Numerically Controlled Lathes and Turning Centers.
9. Japanese standard JIS B-6190 (Japanese equivalent to ISO 230-4, see ref 5 above)
10. Chinese standard GB/T17421.4 (Chinese equivalent to ISO 230-4, see ref 5 above)
11. American Standard B5.54-2005 Methods for Performance Evaluation of Computer Numerically Controlled Machining Centres. Appendix A3 Recommended minimum test set.

About Renishaw

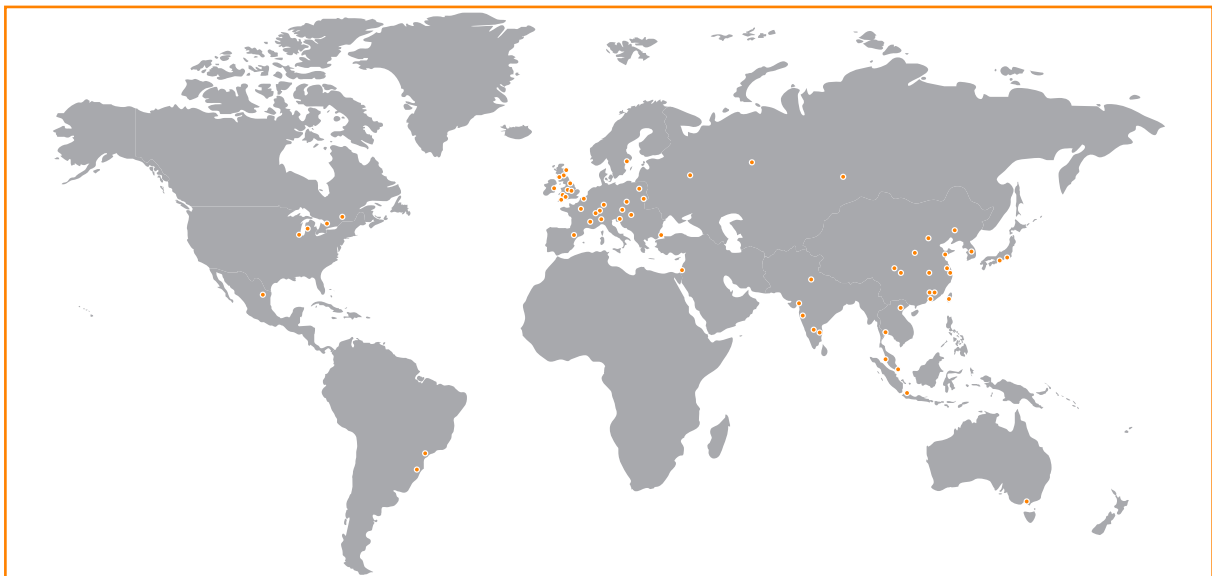
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