FIXTURING FOR ULTRAPRECISION MACHINING OF SPHERICAL PARTS

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INTRODUCTION
Ultraprecision machine tools can generate very high quality spherical surfaces. For example, a cylinder with a spherical end is often used to evaluate the performance of a diamond turning lathe. The spherical surface is sometimes specified slightly past the equator to test how well the control system and machine handle the x-axis reversal (producing what is sometimes referred to as a “trailer-hitch ball” test part). A good machine can produce a spherical hemisphere (half of a full sphere) true to less than one μm, and if a diamond tool is used on an aluminum blank, a very shiny half sphere can be produced. A significant challenge arises when it is necessary to generate a full sphere—how do you hold on to one hemispherical surface while generating the other half? The two hemispheres must align very precisely to produce a true full sphere. The same problem arises when making spherical shells—if you first machine the outer radius, how do you hold on to the shell to make the inner radius and produce a uniform wall thickness?

This paper discusses the effects of the holding fixture precision on the overall part precision when machining a full-sphere or a hemispherical shell. Even if the machine tool generates a perfect hemisphere, a small error in the size of the spherical fixture (referred to as a pot chuck) holding the part for the second machining operation can produce a significant error in the alignment of the two hemispheres.

PROCESS STEPS
There are different procedures that can be used to produce spherical parts. A common process using an ultraprecision computer numerically controlled (CNC) lathe is described here. This process has many advantages; however, it is not the only process that can be used. Spheres can be produced by lapping and polishing, for example, but even then it is sometimes desirable to generate a very accurate full spherical blank before lapping. Also, a CNC lathe can generate thin walled hemispherical shells that can not be produced by lapping processes. The lathe process described in this paper involves generating a spherical end on a cylindrical blank and then turning the blank around and holding the spherical end in a chuck while machining the second half of the sphere. This process is illustrated in Fig.1, Fig. 2, and Fig.3.

FIGURE 1. Step one of a full sphere machining process.

FIGURE 2. Vacuum Pot Chuck.
STEP 3: Machining second half of sphere.

FIGURE 3. Machining second hemispherical surface.

**Machine errors in producing spheres**

The hemi-spherical surface is generated by programming a radius tipped tool to pass through a circular path in the x-z plane while the blank is turning about the spindle axis (usually referred to as the z-axis). The quality of the sphere in a pole-to-equator path depends on how precise the machine tool can generate a circular path. The truth of rotation of the spindle axis determines how precisely the resulting hemisphere is about any latitude sweep. How accurate a circular path the lathe can generate in the x–z plane determines how accurate the hemisphere is in the polar direction. The machine tool parameters and measuring methods used for machining the vacuum pot chuck are the same that are used for making the hemispherical part.

The case considered in this paper is for a lathe that can produce a near perfect circular path in the pole to equator direction, and has a near perfect spindle error motion. (That is to say that the machine tool can generate a hemispherical part far better than the sphericity requirement.) The case considered here is when, even though the lathe can produce a near perfect hemispherical surface, there is an uncertainty in the size of both the first hemispherical surface and the spherical cavity in the pot chuck—both can be perfect spheres but differ slightly in actual spherical radius.

In some cases the pot chuck can be made to fit almost perfectly to the hemispherical surface of Step 1 by special in-process measurements and carefully fitting each pot chuck to its unique hemisphere. However, the case considered here is the challenge when controlling or automating the process. How accurate does the process (machine tool positioning, tool set, etc.) need to be to make the part within tolerance without special fitting of the pot chuck to the first hemisphere?

If the pot chuck is slightly smaller than the part, a final “full sphere” will have a slight difference between the pole-to-pole height than twice the equator diameter as illustrated in Fig. 4.

**CONCLUSIONS**

The case where the pot chuck is slightly smaller than the first operation hemispherical surface is important in many spherical part manufacturing situations. The discussion presented here suggests that the accuracy requirements for the machine tool and associated process is driven more by the match of the fixture to the part than by the sphericity tolerances of the part itself.

FIGURE 4. Full sphere machined as two hemispheres—some misalignment possible.

There are some process changes that would impact the final shape. For example, the process could be set up to ensure that the part be slightly smaller than the pot and always bottom in the pot; however, then the uncertainty of the size might allow the part to shift to one side during the machining that would produce a mismatch in center line between the two hemispheres. Also the case where the part is ensured to hit bottom can produce a situation where the part is not held tightly enough and can slip in the pot chuck during machining.