New Technology and Novel Design make Sub-Micron Production Practical

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Introduction

This paper is based on the design and testing of the Cranfield Precision DeltaTurn40 lathe (Figure 1). This machine has been designed as a small chucking lathe for sub-micron production turning of complex parts in conventional materials and also hardened tool and bearing steels.

Initially, we will describe in detail how several new novel technologies have been brought together to challenge the way current machines are designed. We will then show how, in production, the machine is capable of producing parts with sub-micron size control at capabilities greater than $1.67\ C_{pk}$. The paper also presents results from on-going hard turning tool trials showing how the machine can obtain excellent surface finishes and hence challenge conventional grinding processes, even when bearing ratios are required that conventionally could not be achieved with turning.

Technical Developments

Due to the small size of the machine several novel technical developments were brought together making a unique machine tool that overcomes most of the errors normally found in precision machine tools.

The key elements brought to the machines design are:

- Voice coil motors
- Two axis encoder
- Hydrostatic bearings
- Space frame construction

Figure 1: The DeltaTurn40

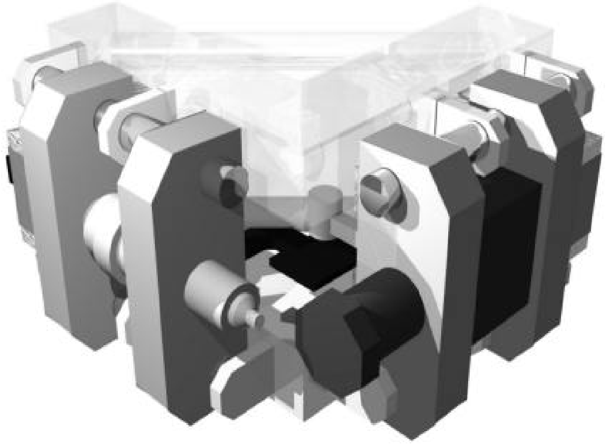


Figure 2: Construction

Voice Coil Motors - Based on the moving coil actuators used in loudspeakers, voice coil actuators apply linear force to both the X and Z axes on the machine. Linked with high-speed digital signal processing (DSP) they provide high dynamic performance, coupled with zero wear parts. Benefits include precise, frictionless positioning, high acceleration and stiffness, and also freedom from backlash and lateral disturbance - unlike conventional ballscrew drive systems. The motors are positioned to apply motive force directly onto the centre-line (and centre of gravity) of each axis to drive the workpiece and turret axes. The intersection of the force vectors also falls within the working volume of the machine.

Two Axis Encoder - The axis positioning system comprises a Heidenhain [1] grating plate with orthogonal graduations and reference marks (sometimes referred to as a tartan scale) and a non-contacting scanning head that detects reference and motions in both X and Z directions. On this machine the scale is mounted on spindle centre-line, off to the side of the Workslide Z axis, with the scanning head mounted off the side of the Toolslide X axis. With the system measurement point placed in this configuration, as close as possible to the cutting point and at precisely workpiece centreheight we are able to eliminate virtually all Abbé errors [2]. Several advantages quickly come to mind when utilising this system: -

- Axes positions measured directly and with reference to each other – <u>not looped through base structure</u>.
- Each axis motion is measured not only in the critical direction but also orthogonally, therefore any lateral or yaw error motion on either axis is sensed and is automatically corrected by the other axis.
- Orthogonality of machine axes is permanently determined by the precise grid pattern alignment on the encoder plate and can, if required, be further error corrected in software. Precise physical axis alignments are not required.
- No forces in the machine measuring loop.

Hydrostatic Bearings - The machine utilises round bar temperature controlled hydrostatic bearings on both linear axes, with a kinematically constrained (but not over constrained) configuration of pads, equispaced above and below the axis centreline to provide precision with ease of manufacture and assembly. The Workspindle can be specified with either air or hydrostatic bearings depending on the application. Hydrostatic bearings are utilised for smoothness of motion, high damping, high static and dynamic stiffness and enduring precision.

Space Frame Construction - Both axes on the machine are of lightweight construction to permit maximum acceleration. The axes are attached through the hydrostatic bearings to a triangulated space-frame 'Delta' base construction as shown above in Figure 2. This structure is supported on a system of isolation feet to the machine's enclosure. This base has been designed utilising FEA techniques to optimise placement and type of structural materials used to give a stiff, damped structure with a minimum of mass – the first measured natural frequency (highly damped) was 350Hz. This configuration allows for a compact machine design that can accommodate all the services for air and hydrostatics within its own enclosure without affecting the performance of the machine.

Tool Turret with Error Correction - To provide the capability of multiple operations on a part, the machine is fitted with an 8 position tool turret. To eliminate any machining errors due to non-repeatability of index, variation in the indexing positions are logged in both the X and Z planes and correction factors applied.

Production Manufacturing

Process Control - To maintain the consistency of size despite process related effects, (particularly tool wear) the automated part handling places each completed part in an integrated, dedicated air gauge measurement device with 0.1µm resolution of size for 100% inspection. Data for each of up to 5 critical features (OD, ID or length) is analysed for trend and correction factors are fed to the CNC controller for analysis and consequent change to tool position offsets. Detrimental middle-to-long-term thermal drifts are thus prevented from causing size fluctuation. Statistical Process Control techniques are applied to the finished part measurement data to monitor performance.

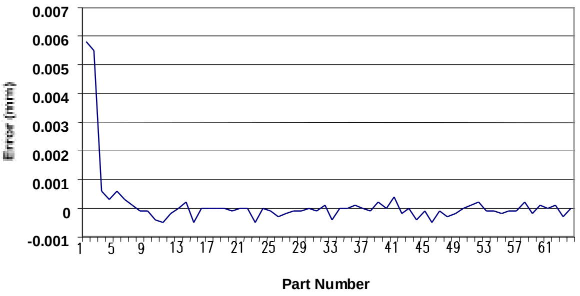


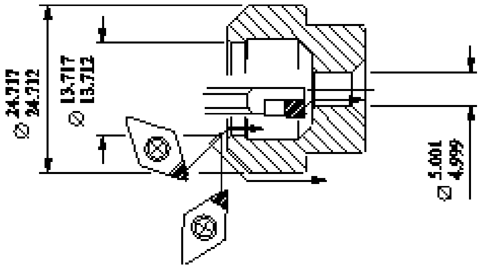
Figure 3: Diameter error log

Additionally, cutting force monitoring (X and Z) can be used to identify tool failure and to monitor the onset of tools reaching the end of their useful life. This all helps to make highly accurate extended production runs straightforward: Any error from the first part is applied 100% to the tool offset data to approach a correctly sized third part (part 2 is being machined whilst part 1 is being measured). From this point onwards an 8 part moving algorithm is used to control size variation due to tool wear and environment changes.

The chart in Figure 3 shows the measured size error, for the finish boring of 430F Stainless Steel to $\varnothing\ 5mm$. The processing was at $70\ {}^{m}/_{min}$ surface speed (V_c) with a feedrate (f) of $0.03\ {}^{mm}/_{rev}$ and $50\ mm$ depth of cut (*doc*).

It also shows the part size being established, and subsequently maintained for the production run.

The example below shows the ability of the machine to perform hard turning operations (replacing costly and time consuming grinding operations). CBN tool technology is used for the hard turning of steels, generally above *58 HRc*: both conventional and stainless steels have been processed on DeltaTurn. These processes are 'dry cutting', requiring no coolant or cutting lubricant, thus eliminating the environmental hazards of the removal and disposal of these fluids and compounds.



Material: 535A99 BS970: Part 1: 1983 (EN31), through hardened to *58-62 HRc*

- V_c = 225 $^{m}/_{min}$ (170 $^{m}/_{min}$ for 5 mm bore)
- f = 0.03 $^{mm}/_{rev}$
- *doc* = *0.05 mm* (2 passes)
- Standard Sumitomo CBN tools: -
- Inserts: DCMW070204BNX10NU
- Brazed tip bar: BNBB04BNX20

Figure 4: Component and data

Post-process analysis of the completed components displayed roundness errors of < *0.2 mm*, and concentricity errors between features of < *1 mm*. Surface Roughness values were achieved (in the hard turning of steel) to better than *100 nm* R_a. Such high quality roundness errors improve the part (∅) accuracy capability. To achieve the accuracies quoted within this paper it is important that sufficient stock is left on the component critical features prior to finishing to allow 2 cuts. The first cut is to clean up the part (to < *1 mm* run-out) which then allows the second cut (at consistent pressure) to achieve the excellent (< *0.2 mm*) roundness levels.

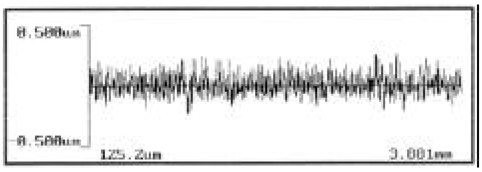


Figure 5: Bore surface roughness

The roughness trace shown in Figure 5 is from the *5 mm* bore of the part shown in Figure 4. The finish obtained was *75 nm* R_a. The machine has also been used with both PCD and natural diamond tools (on non-ferrous materials) to achieve roughness values of *~30 nm* R_a

Surface Finish - Recent work carried out on the DeltaTurn40 in co-operation with several industrial partners has proven the capability of the DeltaTurn40 not only to manufacture components with nanometric surface roughness, but it is also possible to maintain low surface finishes throughout the tool life. Typical surface finish requirements for precision components are between *100-200 nm* R_a, sometimes with a combination of different finish parameters being requested (e.g. R_a and bearing ratio).

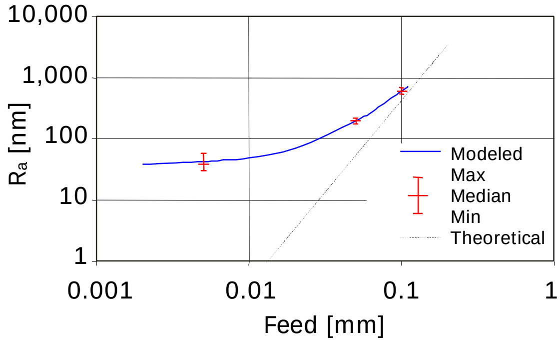


Figure 7: Finish vs. Feed (0.4 mm rad tool)

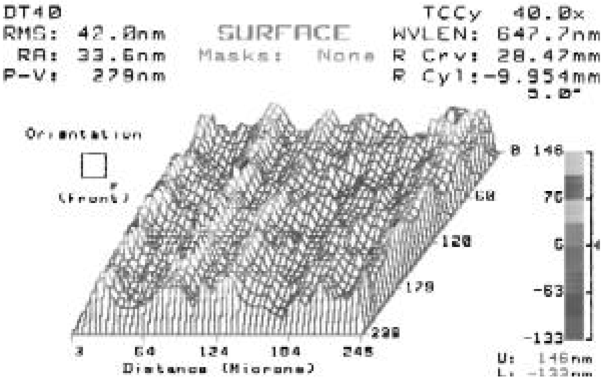


Figure 6: Surface plot of a turned component
R_a = 33 nm

A statistically designed set of experiments has been carried out on DeltaTurn40 in co-operation with De Beers Industrial Diamonds UK to prove the machine's capability to achieve low surface finish values [3].Figure 6 shows a 3D-plot of a component machined during these experiments recorded with a 3D optical surface profiler. At low feed rates it was possible to achieve surface finishes down to *31 nm* R_a. Statistical evaluation of the data gathered so far reveals an average surface roughness of *42 nm* R_a (Figure 7), at suitable cutting conditions.

The disadvantage encountered when manufacturing these very good surfaces is the requirement for a low feed rate. The low feed rate not only increases cycle times, but also increases the contact time between tool and workpiece.

Since tool wear in CBN cutting tools is roughly proportional to the contact time only a small number of components can be machined with any one tool. Combinations of higher feed rates and larger tool radii allow the manufacture of surface finishes in the order of *100 nm* R_a while reducing machining time by a factor of 20. This in turn increases the number of workpieces, which can be machined per cutting tool.

Tool life tests carried out on DeltaTurn40 show that under typical machining conditions CBN tools have a life in excess of *40-60 min* in contact with the workpiece. This exceeds tool manufacturers' tool life data (typically *30-45 min*) by a significant margin. During the tool lifetime surface finish drifts as the tool wears, but can be maintained within acceptable limits. Only when excessive tool wear occurs can a rapid drop off in surface finish be observed.

Modified surface finishes - The degree of process control achieved on DeltaTurn40 not only allows for very precise size and finish control, but also allows the designer to tailor the surface of the part in the sub-micron level as shown below.

Figure 8: Synchro Cone

The taper of a Synchro cone normally has a specification for surface finish (R_a) and bearing ratio (*tp*). Bearing ratio is the length of bearing surface (expressed as a % of the measured length) at a specified depth below the highest peak of the surface and can be difficult to achieve with a turning process. On analysing the requirements it was found that by modifying the tool path in the sub-micron level the required finish could be achieved. The image below (Figure 9) shows a typical pattern used for Synchro cones, the surface has > *1 mm* deep grooves equispaced along the surface. The depth, length and spacing of these grooves is critical to bearing ratio, where as tool rad and feedrate determine the overall surface finish of the feature.

Figure 9: Surface image

Process trials – the next stage - Further work will focus on achieving the best level of surface finish while maintaining economic production rates, tool life and bearing ratios and will also look at interrupted cuts and better exploitation of the wiper tool geometry in achieving best possible surface finishes.

Conclusions

The above results have shown that by taking a global approach to machine design and applying optimised process parameters, sub-micron manufacturing tolerances at better than 1.66 capability ratios, with part roundness of *0.1 mm* and surfaces finishes below *75 nm* R_a are readily achievable in an automated production environment. The materials can be ferrous and non-ferrous, and can include hardened bearing and tool steels. Further work is now underway to use the DeltaTurn40 as a diamond turning machine including adding a vacuum chuck and optical toolset station.

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1 Heidenhain, “Turning on a Micron”, Drives & Controls, page56, Sept. 1998

2 Bryan,J.B. “The Abbe Principle Revisited: An Updated interpretation”,
Precision Engineering, Vol 1, pages 129-132, 1979

3 M. Knuefermann, R. Read, R. Nunn, I. Clark, M. Fleming
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