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# New diamond turning strategy with 2-axis fast tool for dense dimple pattern on embossing rollers

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**Abstract**

Transparent structured polymer foils are applied presently in most large-scale displays and TFT-screens as anti-reflection or anti-spy films and light guiding elements. These optically functionalized films are typically made of thermoplastics by a large-area hot-embossing process from roll-to-roll. For the manufacture of optical-grade structured embossing rollers by ultraprecision diamond machining KUGLER GmbH has developed the hydrostatic drum turning lathe TDM-2000. Besides the standard diamond tool holder different fast tool servos (FTS) are available for generating a variety of surface structures with optical quality. Special proprietary CAM-software assists the machine operator in creating NC-programs for producing periodic gratings, crossed gratings, gratings with a superlattice, regular and random dot patterns as well as patterns from elongated structure elements up to trapezoidal and even freeform shapes. An import function enables usage of customer pattern location files and grey shade bitmaps whose grey levels are converted to locally varying infeed. A new dual-axis FTS with 1,5 kHz bandwidth piezo drives for 40 µm infeed stroke and 75 µm motion parallel to the roller axis enables up to 800 dot structures / second, 2D-wave patterns and quite unusual shape geometries. Different types of new structure patterns will be presented which could be interesting for structured plastic foil applications in decorative lighting and as anti-counterfeit elements in safety engineering.

Keywords: Ultraprecision turning lathe, ultra-precise machining of embossing rollers, large scale surface structuring for R2R-technique, microstructure replication by embossing, structured surfaces to effect function, 2-axis fast tool servo for ultraprecision machining

## 1. Introduction

Presently important industrial application fields for transparent structured polymeric foils consist in large-scale displays, TFT-screens, anti-reflection or anti-spy films and light guiding elements for lighting. These optically functionalized films are typically made of thermoplastics by a large-area hot-embossing process from roll-to-roll, applying structured roller dies up to 2 m length. A precondition for achieving optical surface quality on the film is an ultraprecision-machined roller surface. Based on a longstanding experience in ultraprecision machining and machine engineering for microcutting the KUGLER GmbH has developed the hydrostatic drum turning lathe TDM-2000 whose design principle, setup and processing techniques are presented.

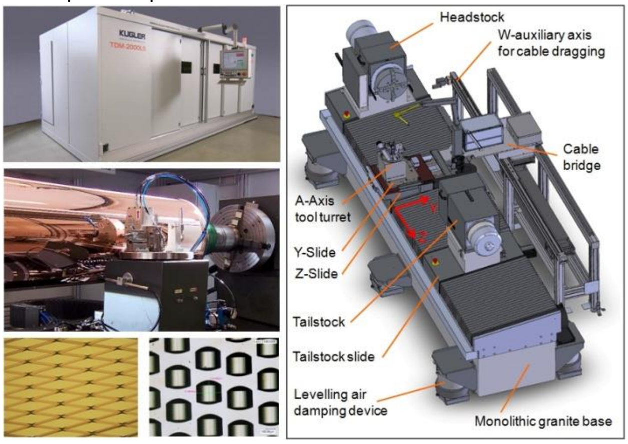


**Figure 1.** Design and setup of the drum lathe TDM-2000.

It features a hydrostatic Z-axis with 2400 mm travel length for moving the machining tools along the Cu- or NiP-plated rollers. Besides the adjustable standard diamond tool holder a fast jerk-compensated milling axis and 2 different fast tool servos (FTS) are available for generating a variety of surface structures with optical quality. Special proprietary CAM-software assists the machine operator in creating NC-programs for structure generation. A new dual-axis FTS with 1,5 kHz bandwidth piezo drives for 40 µm infeed stroke and 75 µm motion parallel to the roller axis enables up to 800 dot structures / second, 2D-wave patterns and quite unusual structure pattern.

## 2. Design principles and processing techniques

For manufacturing microstructured embossing rollers with usable length up to 2 m and diameter up to 600 mm highest demands exist regarding machine engineering and processing techniques. Machining and structuring of such rollers to optical quality normally is done by means of diamond turning and shaping. The design of the roll turning machine TDM-2000 shown in figure 1, relies on a monolithic granite base and motion axes with hydrostatic bearings. The Z-axis with 2400 mm travel length for moving the machining tools along the Cu- or NiP-plated rollers features straightness deviations of ± 2.5 µm (horizontal) and ± 6 µm (vertical) at 2200 mm stroke as well as a relative positioning accuracy of ± 0.1 µm. Other specifications are given in the table below. Conventional diamond turning is applied for pre-machining the rollers to perfect cylindricity and roughness Ra < 5 nm and also for V-groove structuring by means of plunge or spiral cutting.

| Specification | TDM-2000 Drum Lathe |
|---|---|
| Type of bearings | Completely hydrostatic |
| Drum mounting capacity | max. values: length 3200 mm, diameter 600 mm, mass 3000 kg |
| Machinable length/Z-axis travel | 2200 mm |
| Positioning accuracy Y-/Z-axis | ± 0,1 µm (bidirectional, relative) |
| Speed of motion Y-/Z-axis | 1500 (Y) / 2000 (Z) mm/min |
| Headstock main spindle speed | 0 – 600 rpm |
| Rotational bearing runout | ≤ 0,25 µm axial/radial |
| Main spindle pos. accuracy | ≤ 1 arcsec in indexing mode |
| Straightness of linear axes @ full stroke | Y: ± 1 µm (horiz./vert.) @ 300 mm<br>Z: ± 2,5 µm (horiz.) / ± 6 µm (vert.) @ 2200 mm |

Pyramid structures can be produced as crossed gratings either by combining an axial linear grating with a turned plunge cut grating or by crossing 2 or 3 spiral cuts with low slope. In addition to the adjustable standard diamond tool holder different fast tool servos (FTS) are available. Due to the detrimental effects of thermal fluctuations processing times have to be kept short. Application of an FTS as fast and dynamic axis for the tool infeed is a well-proven means for saving processing time. The FTS-devices differ in stroke and dynamic bandwidth. One single axis FTS can move the tool tip up to 400 µm at ≤ 600 Hz for small and ≤ 100 Hz for full stroke whereas the second one is much more dynamic with up to 40 µm stroke and 1.5 kHz bandwidth. Latter relies on the own development of a dual axis FTS-40/75 which can move the diamond tool also parallel to the roller axis up to 75 µm. In contrast to a similar system described in [1] which is based on an extended flexure mechanism with limited strokes of 27 µm (axial) and ± 8 µm (transversal) the KUGLER solution incorporates two commercial piezo-actuated micro-stages in a stacked arrangement (figure 2).

### 3. CAM-Software for structure generation

Two special proprietary CAM-software modules, the V-groove and pattern generator KVG and KPG assist the machine operator in creating NC-programs for producing periodic gratings, crossed gratings, gratings with a superlattice, regular and random dot patterns as well as patterns from singularized, elongated structure elements up to trapezoidal and even freeform shapes. The KVG specially creates NC-programs for different V-groove structures which may include a superlattice like "1 high / 5 low" and are produced by plunge cuts, single spiral cuts or multi spiral cuts.

The KPG pattern generator software shown in figure 2 allows definition and tuning of dot-like structure shapes and creates NC-programs for pattern based on customer location files. Latter normally result directly from special optics design programs as a 2-column ASCII-file with X-Y-coordinates. After import to the KPG these first are transformed to C-angle coordinates for the main spindle and linear Z-coordinates for the tool slide which are sorted for increasing C-angle in order to generate a continuous spiral. In case of the dual axis FTS (V-W-axes) the data are then analyzed wrt. possible side steps of the tool during the move to the next C-position. If compatible with the fast dynamics of the Z-parallel W-piezo actuator side steps will be executed. The shape of the structure element can be defined within the KPG if it is dot-like or trapezoidal. Shapes with a freeform profile can be imported as a file too. Shape profiles are checked for feasibility by means of the Fourier-spectrum wrt. the bandwidth of the FTS and the steepest slope wrt. compatibility with the predefined tool geometry.

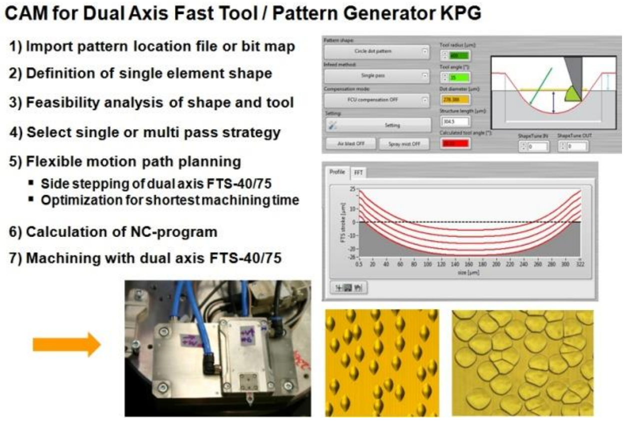


**Figure 2.** CAM-software for dual axis fast tool program generation.

Prior to the NC-code calculation single or multi pass machining has to be selected and defined. NC-Programs start with a header part on which the pattern location part follows.

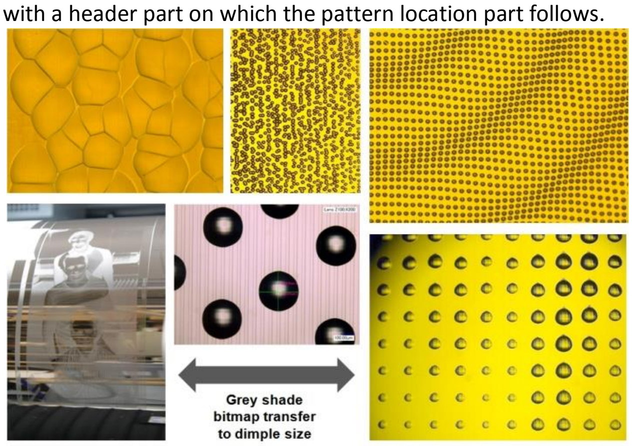


**Figure 3.** Different dot pattern created with the pattern generator.

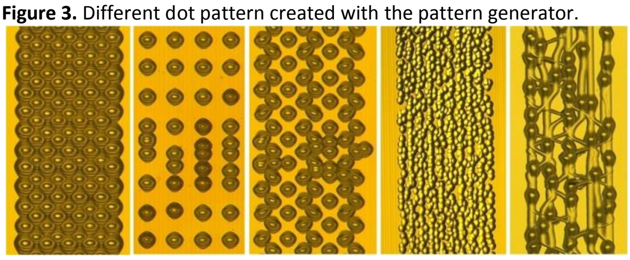

**Figure 4.** Dot pattern for use in digital coding and trademarking.

Main information of the header is the shape of a single structure element which is loaded into a separate V(C)-table (resolution dC = 0.00014°) of the 24 kHz open-loop driven FTS V-axis normal to the roller surface. When the C-axis arrives at the starting point of a structure element the V-axis amplifier is controlled according to the V(C)-table and the actual C-speed to execute the shape. In order to enable superposition of shapes the V(C)-table can be duplicated and started again by turns before the first shape is finished. The pattern location part only contains the C-axis trigger positions for the shapes and the side step lengths for the 2$^{nd}$ W-piezo actuator. In this reproducible way the structures in the upper line of figure 3 and of figure 4 were machined. The pattern location import function also enables usage of grey shade bitmaps whose grey levels can be converted to locally varying infeed (lower line figure 3). In this case the NC-program then contains a 3$^{rd}$ row with percentage values for the maximum infeed depth.

### References

[1] Zhiwei Zhu et al., 2014, *Precision Engineering* 38, 809