Introduction

In the last years one can find a strong reorientation of most microscopical methods to study objects in natural (or adjustable) conditions without preparation. Microscopical visualization without vacuum and coating allows maintaining the natural specimen structure as well as examining its behavior under external influences (loading, chemical reactions, interaction with other solids, liquids, gases etc.)

Another important issue for modern microscopy is the three-dimensional information. Most existing microscopes can visualize either the object surface or a transmission image through a thin section. That means the three-dimensional internal object structure can only be investigated destructively. Even with the most delicate preparation or cutting methods the specimen structure can change dramatically. For living or exceptional objects any cutting is not even possible.

One more significant aspect of modern microscopy is the quantitative interpretation of the images in terms of the microstructure of the object. Although most microscopes include or can be combined with powerful image processing systems, the interpretation of the contrast is still the main problem. On the other hand, reliable micromorphological information could be easily obtained from a set of thin flat cross sections which reveal only density information, from which case accurate two- and three-dimensional numerical parameters of the internal microstructure could be calculated.

Considering existing microscopical techniques, one can find that non-destructive information from the internal structure of an object in natural conditions can be obtained by transmission X-ray microscopy. Combination of X-ray transmission technique with tomographical reconstruction allows getting three-dimensional information about the internal microstructure [1-3]. In this case any internal area can be reconstructed as a set of flat cross sections which can be used to analyze the two- and three-dimensional morphological parameters [4]. For X-ray methods the contrast in the images is a mixed combination of density and compositional information. In some cases the compositional information can be separated from the density information [5]. Recently there has been a significant improvement in the development of X-ray microscopes using synchrotron sources. However, these facilities are rather complicated and expensive and are not accessible for most researchers. On the other hand, the last few years have shown also a steady improvement in X-ray source technology so that now inexpensive compact sealed X-ray microfocus tubes can be produced with a very long lifetime. Because these sources emit polychromatic radiation one cannot use X-ray lenses for optical magnification. However, since the source spot size is small one can project the
object over a large distance to the detector so as to obtain a geometrical magnification. In that case spatial resolution is limited by the X-ray spot size. At this moment, the attainable spot size is of the order of 8-10 micrometer but with the steady technological improvement one can expect submicron X-ray sources in the coming years.

**Description of the system**

A desktop X-ray micro-CT system SkyScan-1072 has been developed for the general-purpose non-destructive 3D-microscopy. It consists of a microfocus sealed X-ray tube 20-80kV/100uA with 8µm spot size and expected lifetime >10000hours, a precision object manipulator with two translations and one rotation, an X-ray CCD-camera with cooled 1024x1024 pixels 12 bit sensor fibre-optic coupled to high-resolution scintillator. The computer processing and system control are done with internal Dual Pentium II 333MHz / 384Mb RAM / >8Gb HDD / CD-writer operated under Windows-NT 4.0. The X-ray magnification ranges between 4.5 - 120. For microtomographical reconstruction transmission X-ray images are acquired from up to 400 rotation views through 180 degrees (or 800 views through 360 degrees) of rotation. In order to study high-density materials the system can be supplied with a 130 KeV / 300 uA sealed tube with a focus spot size which can be selected at 10 µm or 40 µm.

A software package has been developed for system control and microtomographical reconstruction. The microtomographical reconstruction algorithm is based on the filtered back-projection procedure for fan-beam geometry with specific noise-reduction corrections. The software and hardware were optimized with respect to speed running in optimal 32 bit MS Visual C++ 5.0 and tested on different Intel and DEC processors operating under MS Windows-NT 4.0. The reconstruction time for one cross-section of 512x512 float-point pixels from 200 projections takes 10 sec in Dual Pentium-II 333MHz and 16 sec in AlphaPC 500MHz. The software can also be used to add microtomographic capabilities to existing commercial X-ray projection systems. It has been tested on X-ray microfocus systems supplied by Philips (Germany/Holland), MediXtec (Germany) and CR-technology (USA). The software package includes also image processing and analysis procedures, stereo-visualization, and pseudo-three dimensional visualization with possibilities of realistic 3D-visualization of reconstructed objects. The Windows-NT facilities allow for network connections.

**Application examples**

The X-ray microtomography has been used for a variety of applications. Most spectacular applications can be found in those areas, where three-dimensional internal structures can only be visualized non-destructively and/or in normal environmental conditions.

A first example of application of microtomography is taken from life sciences. Here X-ray microscopy and microtomography allows to reconstruct the internal three-dimensional microstructure without any preparation and sometimes even of living objects. Fig.1a shows an X-ray transmission microscopical image of bone (femoral head). Several reconstructed cross-sections are shown in Fig.1b. Fig.1c shows the three-dimensional reconstruction of this bone.
Another important application area is the non-destructive defectoscopy of electronic components. Fig.2a shows an X-ray shadow image of a SMC LED. The 3-dimensional displacement of internal parts can only be visualized non-destructively in the tomographic reconstruction. Reconstructed cross sections through this LED are shown in Fig.2b. In the same way most electronic components in plastic and thin metal cases can be visualized. Even small electronic assemblies like hybrid ICs, magnetic heads, microphones, ABS-sensors can be tested by microtomographical methods.

One more application area is composite materials where one wants to investigate the 3D structure and/or reaction to external influences. Fig.3a shows a shadow image of a block of composite material. It consists of an epoxy matrix with glass fibers. The reconstructed cross-sections, shown in Fig.3b, clearly show the fiber displacement inside the matrix. The sample can be loaded in situ to investigate the reaction of matrix and fibers to external strain. Also absorption and transmission by liquids can be visualized directly in three-dimensions. This method has been applied to the study of oil absorption in plastic granules and water collection inside artificial plant grounds.

Another application areas of microtomography are biology and agriculture. Fig.4a shows an X-ray transmission image through the tulip bulb in wet conditions. Damaged area can be found in the surface of this bulb. Fig.4b shows the reconstructed cross section with information about depth of damaged volume.

Conclusions
The state of the art in X-ray technology and computer sciences allowed developing an inexpensive compact instrument for three-dimensional non-destructive microscopy. The technique does not require any specimen preparation. During the investigation the object can stay in environmental or special conditions. Even living objects can be investigated. At present the resolution is somewhat better than 10 micrometer and can be used for objects of centimeter size. Further progress in X-ray sources and cameras allows expecting improvements in spatial resolution and avoiding limitations in object size.

REFERENCES