

## Application of subsurface laser engraving in ultrasonic testing of materials

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### Abstract

Various samples with artificial flaws found application in ultrasonic testing of materials. Some of them are used for education, some for calibration of ultrasonic equipment. Possibility of manufacturing of various reflectors in metal blocks are usually limited to simple geometries like cylinders, flat bottom holes, various grooves or notches. There are also limitations to produce small reflectors deep under the surface. All reflectors manufactured using machining present 100% reflectivity of ultrasonic waves. Alternative to steel samples with machined reflectors is optical glass and subsurface laser engraving. Velocities of longitudinal and shear ultrasonic waves in optical glass are almost the same as in carbon steel. Laser engraving allows to produce inside the glass block almost unlimited variety of reflector shapes, orientations and sizes. Single laser action produces a small, about 0,1 mm long, cracking. Such cracks, situated close to each other, can create various surfaces. Separated cracks spread in the volume can modify acoustic properties of naturally isotropic glass and develop acoustic anisotropy, acoustic noise or locally increase attenuation of ultrasonic waves. Paper presents results of measurements performed on laser engraved samples imitating numerous micro-cracks as in steel subjected to creep, regions presenting high acoustic noise and on various artificial flaws reflecting ultrasonic waves.

**Keywords:** Ultrasonic Testing (UT), personnel training and certification

### 1. Introduction

The original aim of ultrasonic technique (UT) was detection of invisible, inner flaws in metal products in NDT way. Today flaws detection is a everyday practice in various branches of industry, during manufacturing and in service. Another application of UT is determining of mechanical properties of various construction materials.

Both, UT flaw detection and material characterisation, need some kind of calibration specimens or etalon blocks. Various blocks with artificial flaws are used to calibrate ultrasonic equipment for flaw detection and flaw size evaluation. Machining allows to produce in a metal block only simple shape reflectors of ultrasonic waves like cylinders of various diameter and length, flat bottom holes, notches or groves of different cross sections. Similarity of such “flaws” to real defects is rather poor. Spark eroding enables to produce more complex shape reflectors in conducting materials. Limitation of these methods is that, without affecting surrounding material, these techniques cannot produce any reflector inside the solid.

Hence searching for better mock-up production techniques. For example [1] describes thermal technique to produce realistic cracks. Intentionally produced crack can have various sizes and shapes but all of them starts form the metal surface. Paper [2] presents the way to produce inner artificial flaws in ceramic. To obtain inner spherical reflectors of various diameters small spheres of Fe, W and Si were embedded during fabrication into ceramic sample.

Inner flaws can be intentionally manufactured inside the weld, during welding [3]. Their dimensions can be determined by RT method but it is difficult to produce such flaws in a repetitive manner. Special tissue mimicking phantoms are used to calibrate equipment for medical ultrasonography [4]. In contrast to NDT applications these phantoms imitate not only tissues reflecting ultrasonic pulses but also specific frequency dependant attenuation of ultrasonic waves. They are made of various gels and can be tested with longitudinal waves only.

Known techniques used today to manufacture artificial flaws for NDT are unable to produce specific shape reflectors inside the solid, to produce distributed flaws imitating for example scatter of ultrasonic waves or to create specific acoustic anisotropy.

For the first time glass as a material for samples used in UT training was proposed in 2004 [5]. Authors used a holographic-ultrasonic system to detect flaws produced by numerous actions of collimated laser beam in 30mm thick polarized glass plate.

Paper describes application of popular today and cheap subsurface laser engraving technique to manufacture various reflectors of UT waves and to change acoustic properties of glass, as a tool for calibration blocks fabrication.

## **2. Subsurface laser engraving**

One of the few techniques that is able to produce small voids in a solid in a controlled way is Sub-Surface Laser Engraving (SSLE). The generation of small and visible dots inside glass lenses used in high power laser technology was originally a problem known as "Laser Induced Damage." It was found that the glass damage was a result of the phenomena known as Multi-photon Absorption [6]. Today this effect is used in laser 3D engraving to produce various "3D sculptures" in blocks of glass. Usually, each dot generated inside the glass has a form of a branch of micro cracks. These dots are elongated in the laser beam direction. Depending on laser pulse parameters, the dimensions of the individual dots (diameter/length) vary from 0.07/0.1mm to 0.3/0.5mm.

Computer controlled focused laser beams can precisely engrave numerous dots to form easily visible milk-white surfaces inside the glass block. To obtain 3D impression dots are separated and usually spaced no closer than 0.15 mm.

SSLE can be used to generate reflecting surfaces of various sizes, shapes and orientation in a volume of glass. Randomly distributed dots, with controlled density or density gradients, can create regions with higher attenuation or scatter of ultrasonic pulses. Dots intentionally engraved close to each other can merge and form small cracks.

In the initial state, the glass used for 3D engraving is an isotropic material with ultrasonic velocities for longitudinal and shear waves equal to 5600-5800 m/s and 3360-3370 m/s respectively and with a very low attenuation. Compared to the acoustic properties of steel, the longitudinal wave velocity in such a glass is only about 5% lower and the shear velocity about 4% higher. It means that glass blocks with artificial flaws generated by SSLE can be tested with standard ultrasonic equipment and probes of frequencies used in ultrasonic NDT.

## **3. Calibration glass blocks**

### ***2.1 Block with artificial flaws***

Figure 1 presents a prototype block with various reflectors which can be detected with straight-beam, longitudinal wave and angle, shear wave probes. Block dimensions are 100\*100\*200 mm and laser beam direction was along y axis. Reflectors are a sphere (A), cylinder (B), 45° inclined rectangles (C), strips (D) and region of high density dots (E). In region E separated dots were engraved in several, closely spaced layers arranged in plains perpendicular to y axis.

Figure 2a shows magnification of 10 mm diameter sphere. It can be seen that prototype sphere surface is rough and small gaps are visible between dots. Therefore coefficient of ultrasonic wave reflection on the sphere (and other reflectors in the prototype sample) is below 100%

and depends on frequency. For example 2 - 10MHz longitudinal waves propagating in z direction (perpendicular to dots axis), reflects on both upper (closer to the transducer) and lower sphere surfaces as shown in Figure 2b. For longitudinal waves of above frequencies, propagating in y direction (parallel to dots axis), sphere is in practice “invisible”.

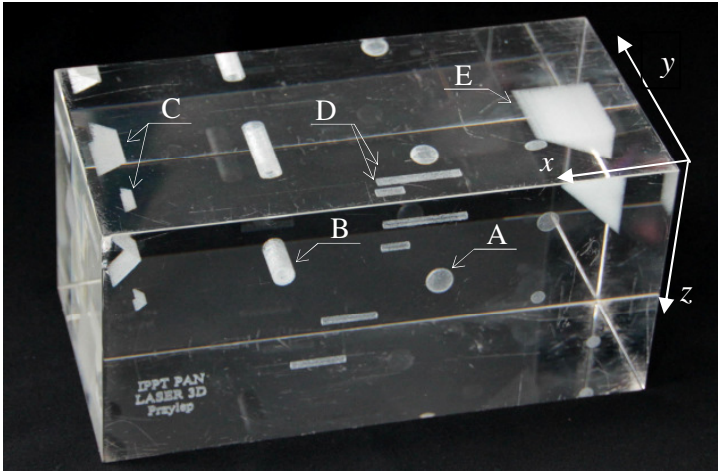


Fig. 1. Glass block (200\*100\*100mm) with artificial flaws of various geometry.

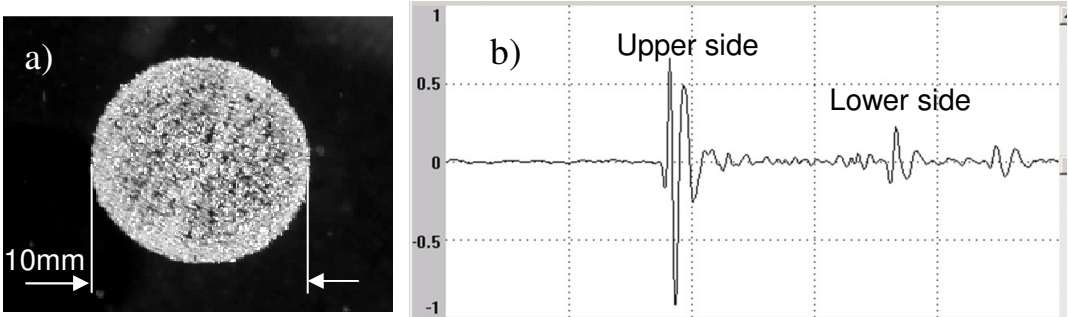


Fig. 2. Laser engraved 10mm diameter sphere (a) and 10 MHz, longitudinal wave reflections (echoes) on upper and lower sphere surfaces (b).

Amplitude of the upper surface reflected signal is 18 dB higher comparing to lower surface reflection.

Next figure presents “acoustic noise” signals (flaw E on Fig. 1) as seen with 2.25 MHz longitudinal wave propagating in z and y directions, obtained for the same gain.

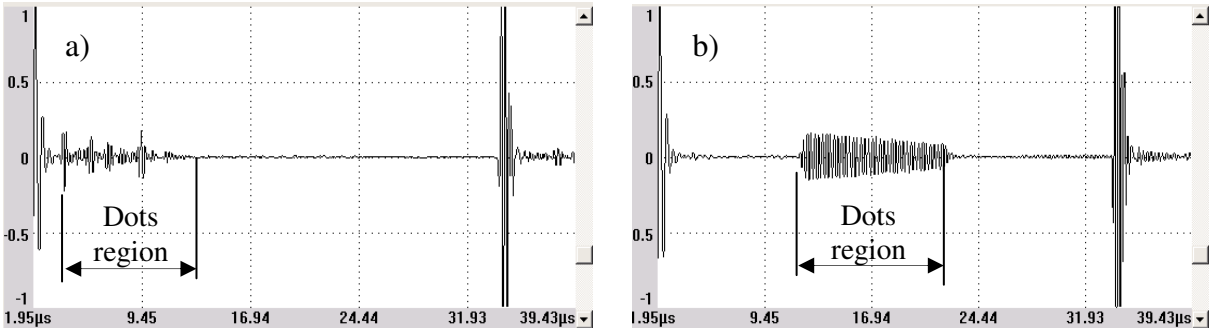


Fig. 3. Echoes obtained on “acoustic noise region with longitudinal waves propagation direction z (a) perpendicular and direction y (b) parallel to laser beam direction.

Signals obtained on “acoustic noise” region show that depending on ultrasonic wave direction versus laser beam action, scatter of ultrasonic waves forms various signals.

## 2.2 Block presenting determined acoustic birefringence

Figure 4 presents glass samples 60 mm thick filled with laser engraved dots. Elongated, much smaller comparing to the wavelength and evenly distributed in the sample volume dots change the velocity of ultrasonic waves depending on dots density.

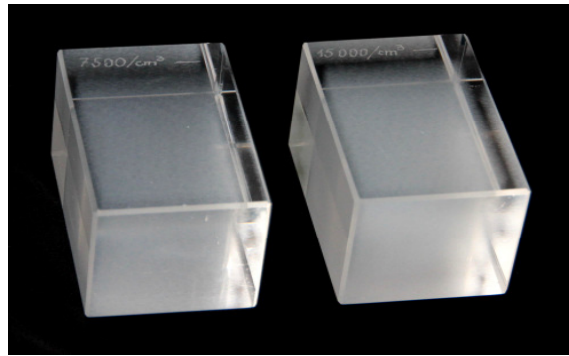


Fig. 4. Samples filled with randomly distributed dots. Dots densities are  $7500/\text{cm}^3$  (left) and  $15000/\text{cm}^3$  (right).

Figure 5 shows dependence of longitudinal velocities for wave propagation direction perpendicular to dots axis (perpendicular to direction of laser beam) on dots density.

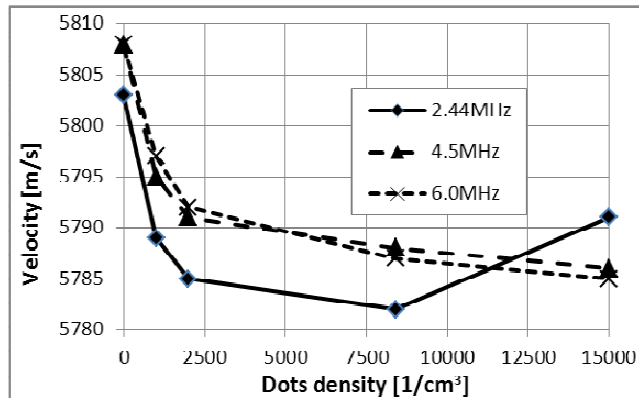


Fig. 5. Dependencies of longitudinal wave velocity on dots density for wave propagating perpendicular to dots.

Elongated, isolated dots do not result in any apparent acoustic noise for frequencies 2-8 MHz but make the sample anisotropic. Shear waves propagating perpendicular to dots axis and polarized parallel and perpendicular to dots propagate in such a sample with various velocities. Depending on dots density one can build a sample presenting particular acoustic birefringence (what is difficult to obtain with metal blocks). For example standard [7] describing UT evaluation of stresses in monoblock railroad wheels, based on acoustic birefringence measurement, describes two blocks for calibration of UT instruments. They are zero stress and 100 MPa blocks. Steel zero stress block can be made as stress relieved annealed fragment of a wheel rim. However blocks demonstrating 100 MPa of tensile or

compressive stress averaged over the block cross section are impossible to manufacture or will be too heavy to handle (whole railroad wheel for example).

Acoustic birefringence is sensitive to material anisotropy due to stress and material texture induced anisotropy. For instrument calibration or periodic checking, assuming constant shear wave frequency, it would be convenient to use stress free samples with material anisotropy equivalent to specific stress value. However it would be very difficult if possible to produce 130 mm thick (wheel rim thickness) steel block of particular texture induced anisotropy.

In several SSLE engraved samples acoustic birefringence was measured with 2MHz shear waves. Wave propagated in the direction  $x$  and was polarized in  $y$  and  $z$  direction. The direction of laser beam, parallel to dots length, was  $y$ . Acoustic birefringence dependency on dots density is presented on Figure 6.

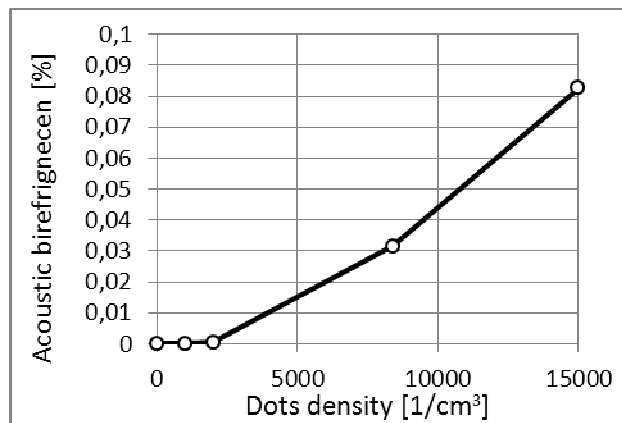


Fig. 6. Dependency of acoustic birefringence on dots density. Measured with 2 MHz shear waves polarized parallel and perpendicular to dots axis.

Acoustic birefringences  $B_{xz}$  equal to 0,03% and 0,082% are equivalent to anisotropies caused by 30MPa and 51 MPa respectively hoop stress in the rim of monoblock railroad wheel (for time of flight of shear wave  $t=83,5 \mu\text{s}$  and elastoacoustic constant  $\beta=-0,79*10^{-5} [\text{MPa}^{-1}]$ ).

### 2.3 Block imitating material degradation due to creep

In the late creep stages, in steel, small, semi-flat and oriented perpendicular to the dominant stress direction voids are created. It was shown on both samples subjected to accelerated creep and on samples cut of piping subjected to long-term creep that such voids can be detected with UT as an increase in the ultrasonic birefringence [8]. However the dependence between voids density and sizes and birefringence value is not known.

As mentioned earlier in SSLE dots are usually spaced no closer than 0.15mm. Tighter spacing of dots can result in crack formation, linking adjacent dots and spoiling the image. Depending on number of laser action and consecutive dots positions, microcracks of various sizes can be produced. From the point of view of ultrasonic testing of materials, such cracks are small, almost flat discontinuities imitating material damage in the late creep stages.

Small microcracks were produced in glass samples 30x30x30 mm [9]. To avoid sample surface damage cracks were formed in a 20x20x20 mm cube inside the sample. In all samples, cracks were distributed randomly in the glass volume and were oriented parallel to one side of the cube.

Figure 8 presents three samples with various densities of cracks ranging from 200 up to 1000 cracks in  $1 \text{ cm}^3$ . For the presented samples, each crack is result of 4 laser actions and the

average crack size evaluated with optical microscopy was about 0.53 mm. Application of 8 laser actions to form one cracks resulted in averaged crack length about 0.9mm. All cracks were oriented more or less perpendicular to the sample  $x$  axis. All elongated “branches” forming cracks in the glass were oriented along the  $y$  axis, i.e. along the direction of the laser beam. Figure 9 schematically presents shapes of microcracks in sample A (4 laser actions/crack) as seen from different directions. A semi-flat shape can be seen looking along  $x$  axis and branches of almost separated, small, very thin, flat cracks along the  $z$  axis. The cross section of each microcrack is the biggest in  $x$  and smallest in the  $z$  direction.

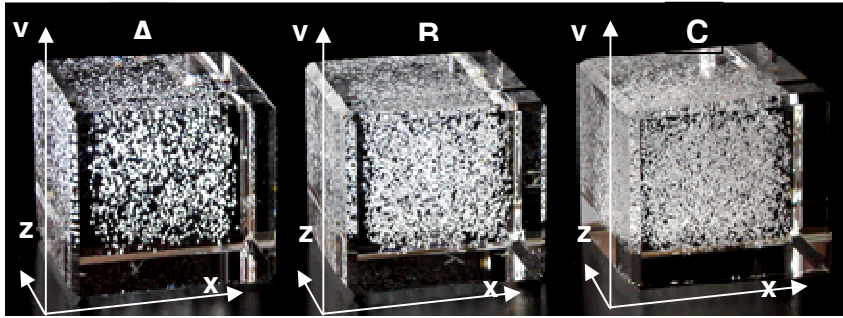


Fig. 8. Glass samples with laser generated microcracks of various densities. Crack densities: sample A –  $200/\text{cm}^3$ , sample B –  $500/\text{cm}^3$ , sample C –  $1000/\text{cm}^3$ .

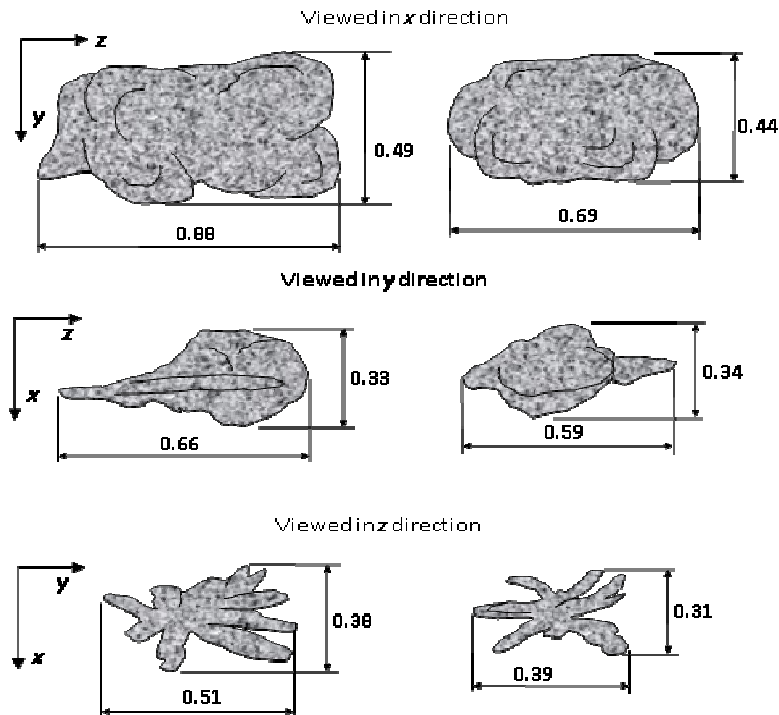


Fig. 9 Schematic shapes of several microcracks in glass sample A, each formed by 4 laser interactions, seen from different directions (dimensions in mm).

Figure 10a shows dependency of acoustic birefringence  $B_{zx}$  calculated as

$$B_{xz} = 2(V_{yx} - V_{yz}) / (V_{yx} + V_{yz})$$

where  $V_{ij}$  denotes velocity of shear wave,  $i$  and  $j$  denotes wave propagation and polarization directions respectively.

Measurements were performed with 2.25MHz shear wave on samples containing cracks formed by 4 laser actions. Figure 10b shows dependence of  $B_{zx}$  on averaged microcrack size.

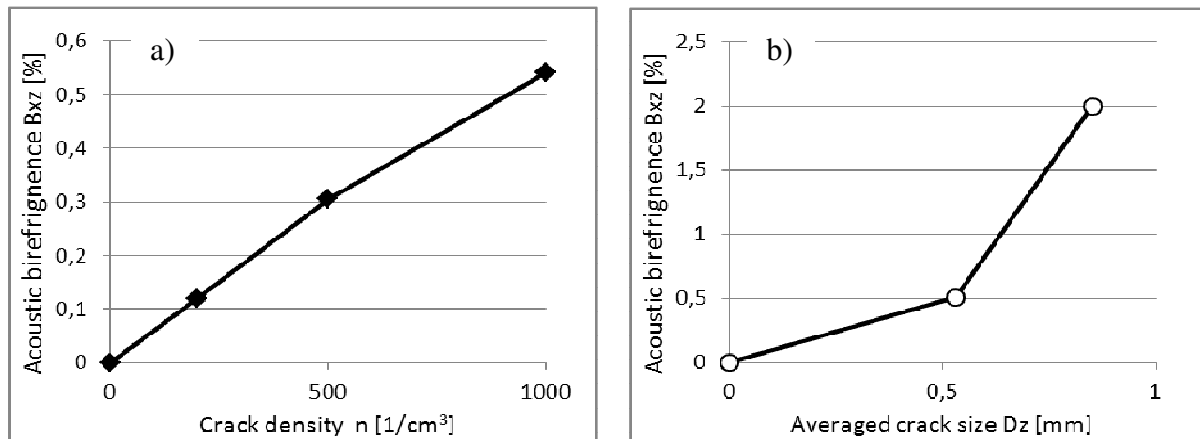


Fig. 10. Dependencies of acoustic birefringence in cracked glass samples on crack density (a) and averaged crack size (b).

Comparing to acoustic birefringences measured on samples filled with individual dots (not “cracked” – see Fig. 4) value of acoustic birefringence in samples with semi-flat cracks is much higher. Bigger dimensions of cracks result also in higher scatter of ultrasonic waves and acoustic noise formation.

#### 4. Conclusions

SSLE in glass blocks seems to be a flexible tool to manufacture solid blocks with various reflectors of ultrasonic waves. It can be used to produce reflectors of arbitrary shapes, to produce specific acoustic birefringence blocks or to imitate material degradation. However preliminary experiments showed several problems to solve. The first one is to obtain surfaces presenting controlled value of reflection of ultrasonic waves. Reflectors in the sample shown on Figure 1 demonstrated much lower than 100% reflection coefficient. Flaws in this sample were composed of 2 layers of separated dots. It was found that clearly visible surfaces composed of dots oriented parallel to longitudinal wave propagation direction are in practice transparent for longitudinal wave even 10 MHz frequency.

The second problem is to increase value of acoustic birefringence in laser engraved glass maintaining low acoustic noise level. To engrave a 100 mm cube filled with dots density  $15000/cm^3$  is time consuming and a value of acoustic birefringence in such a block is equivalent to only 50 MPa in steel. The way to increase laser created dots effect on birefringence seems to be to engrave not separated, short dots but longer chains of dots arranged along a line or to engrave oriented microcracks each composed of two closely spaced dots.

Tests showed that glass samples with various reflectors are adequate tool for UT training. During testing they can be covered with thin opaque plastic foil glued to the glass surface. Such a foil adhered to the smooth glass is not a barrier for ultrasonic pulses generated by both angle and straight beam probes. After training the foil can be removed and all reflectors uncovered and evident for a student. It is also possible to engrave visible but not detectable by UT waves lines dimensioning reflectors. Line composed of single dots is much thinner as compared to the wavelength but still visible in clear glass. It is also worth to remember that in

contrast to artificial flaws machined in metal block, reflection coefficient of ultrasonic waves on SSLE made reflectors, for ultrasonic waves propagating parallel to laser beam action, is close to zero. In results the same glass blocks tested from various sides, will give various results. In theory it is also possible to create various reflectors in a block engraving glass from various directions (to be tested) creating objects “detectable” from one and “non-detectable” from other direction. Modern SSLE machines are able also to produce various shapes not only in rectangles but also in cylinders.

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