

HIGH RELIABILITY, AUTOMATED FIBER RECOAT PROCESS THAT INCREASES FIBER RECOATING YIELDS

Abstract

From restructuring of the telecommunications market, accelerated reduction of component pricing has emerged. High yield manufacturing practices are an important factor to support price reduction while insuring high quality throughput. Improvements in Bragg grating manufacturing have been realized through the development of a novel semi-batch automation process. Although the entire process of fiber handling, from spooling through final packaging is unique, in the interest of time we will focus on our fiber coating reinstatement technique.

Key words: Bragg grating, recoat, coating reinstatement.

Introduction

There are several steps required in the manufacturing process of a Fiber Bragg grating (FBG). Beginning with fiber spooling through final inspection involves up to sixteen steps. Each step introduces the possibility of fiber damage, thereby reducing product yield. Automation techniques have been introduced to minimize fiber handling and potential fiber damage. The introduction of fiber carrousel or trays is gaining acceptance as a method to organize and protect fiber pigtailed during value added manufacturing steps.

Optical fiber coating reinstatement for a FBG requires specifications that are more stringent than a typical fusion splice recoat. Voids, inclusions and other coating defects that might be acceptable in a splice can deleteriously effect the optical and physical properties of the FBG. An added level of difficulty for the recoat process is realized from mid-span coating removal, required for writing most grating types. Approximately 40mm of the original fiber coating is removed via mechanical or chemical stripping or a combination of the two. The quality of transitions created during the strip process, from the bare glass (125 μ diameter) to the typical dual acrylate coatings (250 μ diameter) can introduce features that influence the coating reinstatement process. If the transition is jagged or has overhanging features, air can easily be trapped during coating reinstatement. Similarly chemical stripping can cause undercutting of the primary coating, where air can be trapped. In addition a chemically burned surface does not lend itself to good adhesion of the recoat material.

Structural integrity of the reinstatement transition requires an overlap of the recoat region onto the original fiber coating. This overlap is typically 3 – 5 millimeters. To accomplish this, the recoat is usually 350-450 μ in diameter. This creates a “step” which can serve as an undesirable catch point on the fiber.

Figure 1 is an example of the “step” created at the transition of the reinstatement and original fiber coating.

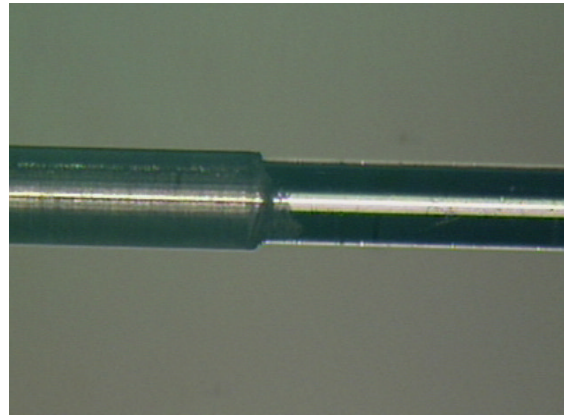


Figure 1

Following recoat, visual inspectors are trained to identify eight types of failures associated with commercially available recoat systems. Flash, channels, gate sinks, delamination, transition cavities, overlap, voids and inclusions, followed by a 200kpsi proof test were part of the inspection process.

Our initial improvement plan focused on quality training programs as well as internal system and coating improvements. The lack of consistent and sustained manufacturing yields pushed the decision to investigate a new approach to coating reinstatement.

Methodology

Evaluation of manufacturing data on coating reinstatement failures, via mold recoat, for FBGs brought out six major faults. Transition voids or bubbles, delamination, inclusions, sinks, overlap, and transition cavities accounted for 30% of rejected product. Of the 30%, air bubbles or voids accounted for 10%. Air entrapment is introduced as the acrylate coating is injected at the center of the stripped region and pushed to the transition areas where it can become trapped. The high viscosity of the acrylate coating (~2750 centipoise) does not allow for easy migration of the trapped air from the coating. Reduction of the viscosity to alleviate this problem introduces further complications as the coating can run out of the cavity, creating undesirable surface voids in the recoat region.

Our approach to resolve the major failure modes was to develop a non-contact method of coating reinstatement. Spray recoat appeared to be a logical choice, in that it could eliminate air entrapment and undesirable features identified with molded recoat. The process needed to be automated, requiring minimal operator intervention, recipe formatted to include recoat length and diameter. Manufacturing process flow requirements needed to be met by having a cycle time of less than five minutes per fiber. Requirements of the chemistry include controlled low viscosity, fast cure, preferably non solvent,

preferably not oxygen inhibited, non toxic, low odor, no interlayer boundaries, and similar thermomechanical properties to the commercial acrylate recoat.

Laboratory Proof of Concept

One obstacle that needed to be addressed was to minimize velocity of the coating as it made contact with the optical fiber. Unfortunately high pressure is necessary to break down the coating formulation into small particles (15-35 μ). These small particles, carried to the fiber by low velocity air are necessary to minimize particle spread on contact, to avoid agglomeration, which leads to beading. Investigation of two alternative methods to air atomization were inkjet and ultrasonic atomization. Although successful, inkjet proved to be too deliberate, as randomization of particle size and placement was necessary to establish a uniform coating. Laboratory experiments proved ultrasonic atomization delivered properties meeting process constraints. A laboratory prototype was designed and built to test process feasibility. An ultrasonic system from Sono-tek Corporation coupled with a high output UV Rocket Spot Cure System from Lesco Incorporated were used as the delivery/cure components of the experimental unit. A linear robot carried a suspended optical fiber holder in front of the atomized coating and cure station. A laboratory syringe pump was used as the coating delivery system. The robot could be programmed for translation speed, position and duration. One ultrasonic head was used, which required the fiber to be rotated on its axis to coat the entire circumference. **Figure 2** View of the prototype system.

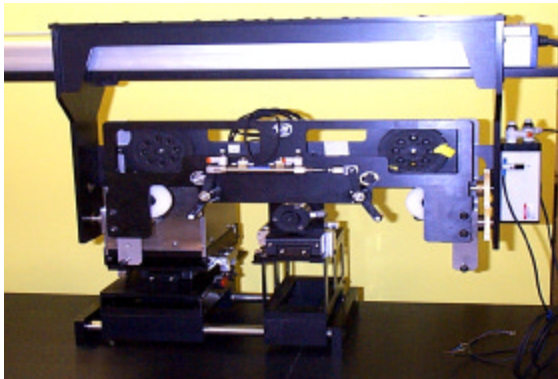


Figure2

Figure 3 is a micrograph of the beginning process of building of cured coating droplets on the surface of a 125 μ diameter fiber.

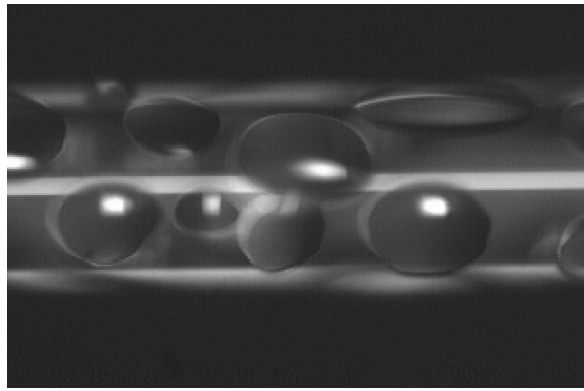


Figure 3

FBGs were successfully coated with this system and tested for optical and physical performance. Although the prototype proved the process viable, forty-five minute cycle times were required for fiber coating reinstatement. Work began immediately to develop a manufacturing system capable of 24/7 operation.

Coating Chemistry

The development of new coatings for fiber optic products requires a careful balance of chemistry and process. By definition, the spray process suggested above involves the jetting of droplets of a coating. Irrespective of the nature of the coating selected, it was anticipated that a viscosity window would be discovered. Formulations too high in viscosity would not “spray” without the application of undue force and/or temperatures, while formulations too low in viscosity would provide layers that were too thin, requiring an excessive number of coating passes to achieve the necessary coated diameter. The development of curing protocols, whereby a recoat would be applied with “x” number of application passes to achieve “y” thickness would also require a constant formulation viscosity, necessitating a formulation with considerable shelf life.

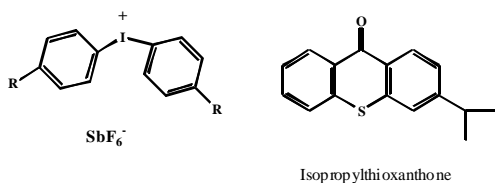
While solvent based coatings are possible for a spray process, a desire to avoid losing processing time in drying out the solvent, as well as the necessity to avoid the generation of voids or delaminations that might occur, led us to 100% solids, UV curable chemistries. Such chemistries are well known in 3M for the generation of adhesives, surface coatings, fiber optics coatings, release coatings, etc. In addition, it was anticipated that a spray process would require containment of the spray, selection of materials with minimal toxicity and low odor were also requirements. A fast cure would also be required to prevent beading or drooping of the coating before the cure was finished.

Adhesion of grating recoat materials to the glass surface of the fiber and to the unstripped coating has long been viewed as important. In a spray process, the issue of adhesion would be further complicated as not all of the material was likely to be applied in one pass. To build up an acceptably thick coating to provide adequate glass protection, the process might well require multiple application steps, each followed by a curing step. This

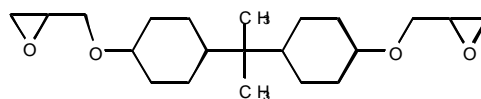
creates the potential for layers, where the adhesion at the interlayer boundary could be called into question. For free radically cured materials applied in an air atmosphere, the well known oxygen inhibition of free radical polymerization would terminate the growth of a free radical polymer (e.g. an acrylate) at the surface of the layer. This would call into question whether a second layer of acrylate applied over the top of the first layer would covalently bind to the first layer. The problem might be avoided by the use of nitrogen inertion, but would introduce additional expense, oxygen detection equipment, purge time, and would limit the access of the operator to the fibers.

The answer to the chemistry question was resolved by the selection of a cationically cured system. Cationically cured epoxies are not inhibited by the presence of oxygen and are known to “dark cure” or continue to polymerize after the irradiation source is turned off¹. At the surface of a first cured layer of epoxy would remain reactive sites, which would copolymerize into the subsequent epoxy layer that was applied. As epoxies are often used as adhesives for optical fibers, the use of an epoxy recoat was hoped to provide adequate adhesion to the glass fiber surface.

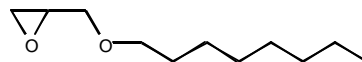
Typical cationically curable epoxy formulations often employ onium salt photoinitiators, such as those commercially available from GE or Union Carbide, or other specialty initiators that have been described in the literature^{2, 3}. Sulfonium and iodonium salts are well recognized as initiators for cationic chemistries. Iodonium salts with a variety of sensitizers, such as isopropylthioxanthone are a well known combination⁴. The spray recoat application effectively employs the sensitized salt combination shown below contained in GE’s product UV9380C.



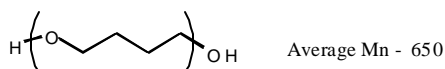
The majority of cationically curable formulations contain materials described as resins, oligomers, and diluents. Although the addition of materials with no functionality is possible, those chosen to date have cationically reactive functionalities, such as vinyl ethers, glycidyl epoxies, and cycloaliphatic epoxies, many of which are commercially available from manufacturers, such as Resolution Performance Products, Aldrich, Union Carbide, and ISP Technologies. Chain transfer materials, such as polyols, have also been employed. Some typical structures of monofunctional, and difunctional materials are shown below:



Eponex1510, "Hydrogenated Bisphenol A epoxy resin"



Heloxy 7, "Alkyl (C8-C10) Glycidyl Ether"



Terathane polyether glycol 650

From a cured materials standpoint, a target of mimicking the properties of commercially available mold recoat materials was required: acceptable elongation (>7%), reasonable modulus and hardness, and avoidance of brittleness or tackiness.

Production System

Several key points were learned from the prototype system.

- Multiple ultrasonic coating delivery head operation would be necessary for uniform coating coverage.
- Coating volume needed to be variable.
- UV cure speed needed to improve.
- Cycle time reduction.

The most difficult obstacle to overcome was cycle time reduction. Our design team came up with a concept that utilized a two-axis system, in which each axis would handle two fiber transport trays. A twenty-minute cycle time would be acceptable to reach the five-minute per fiber goal. The following is a brief description of the primary components and their function in the manufacturing system.

The coating is delivered to a temperature-controlled ultrasonic head via syringe pump, through a hypodermic syringe and delivery tube. **Figure 4** is a cut-away view of the ultrasonic head used for the atomization process.

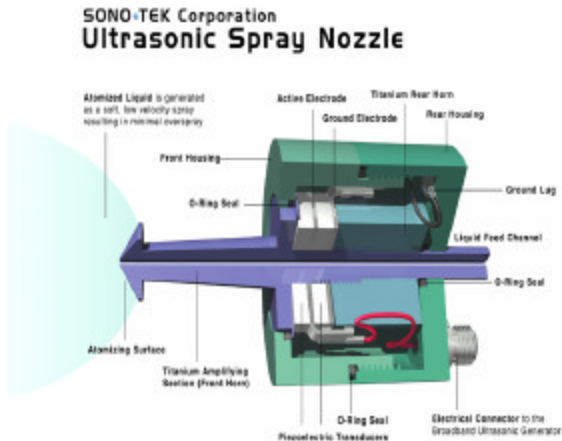
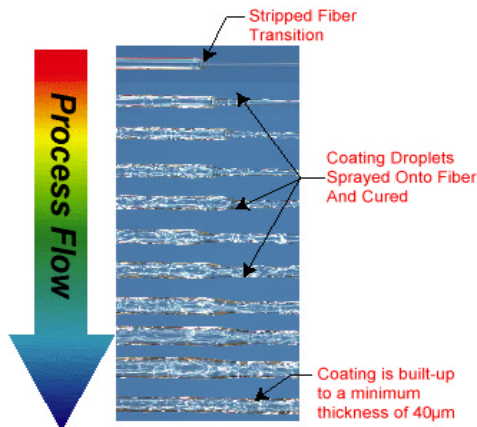


Figure 4
 Temperature control of the ultrasonic head assures consistent coating viscosity throughout the reinstatement process. Once the coating reaches the ultrasonic tip surface, vibration energy is absorbed, causing the coating to atomize.⁵ The 15-35 μ diameter droplets are gently collimated in a nitrogen stream and directed to the fibers. The ultrasonic head, syringe pump and delivery tubing are assembled in a removable coating canister. This is to facilitate easy removal for loading and cleaning. Two coating canisters are used in staggered positions at opposing sides of the fiber for each of the two axis. Catch trays located on each coating assembly unit collect spray, which is not deposited on the FBG. A linear stage holds fiber trays, which carry the fiber in a horizontal position. The fibers travel in front of the atomized stream, about 1.5 centimeters from the ultrasonic head. Each coating pass is followed by rapid UV exposure to cure the deposited droplets. This is an important feature in that we cure the coating quickly to avoid beading caused by coating droplet agglomeration. Up to 100 passes is necessary to reinstate a coating diameter to 300 μ . **Figure 5** depicts build up of the coating in ten passe increments. The final photo is taken from a central section of the recoated fiber. Each pass is independently controlled through an Allen-



Bradley Logix5000 controller. To insure flexibility during development we created a program or matrix. Each line of the matrix independently sets the coating exposure duration, volume of coating, process and cure speeds. This allows the establishment of a finely coated surface, in the beginning of the process, and increased coating volumes later in the process, for more rapid build-up of coating wall thickness. Several programs can be stored in the system and called upon to adjust for coating length and diameter. As discussed earlier, a step from the original fiber coating to the recoat is an undesirable feature. As a result of independent programming of each pass, the coating length can be adjusted during the course of the reinstatement. A trapezoid program can be used which can easily establish a tapered transition, as shown in the micrograph in **Figure 6**.

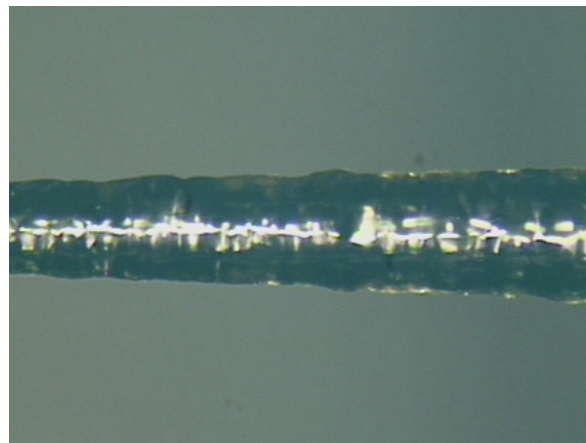


Figure 6
 The large end of the fiber is measured at 400 μ , tapering down to 250 μ . The micrograph in **Figure 7** is a view from the ramp-up of coating diameter to the transition region of the coating reinstatement.

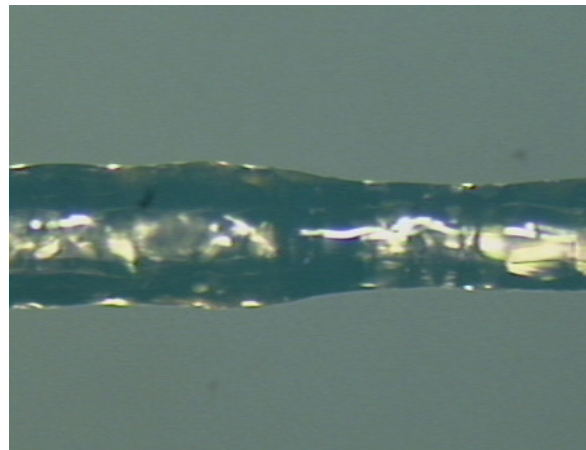


Figure 7
 As stated in the coating chemistry section, this system requires a careful balance of chemistry and process. The process requires low coating viscosity (<300 centipoise) to facilitate ultrasonic atomization. Our low viscosity formulation assists in the easy flow of the coating into undercuts and rough features that often accompany the original fiber coating to glass transition. This has

become an important feature in eliminating any air entrapment at the transitions

Our spray coating reinstatement process is used exclusively on all gratings manufactured on our automation line. The success of this system has led to the development of additional units. **Figure 8** is a view of a single axis system built for manufacturing.



Figure 8

Results

As with any manufacturing process, reliability is crucial to the success of any improvement program. As a result of our novel coating reinstatement process we were able to reduce the number of defect criteria from six to two. Minimum wall thickness and inclusions are the only inspection points required for pass / fail of the coating reinstatement process. Coating concentricity is a function of coating head position and cleanliness of coating and nitrogen supply components. A Mylar test strip is used, at the beginning of a shift, to evaluate the quality of the spray being emitted from the coating heads. The film spray pattern is compared to a standard and a checklist is available to correct any deviation from a normal pattern. Internal alarms for electronic, nitrogen / air supply hook-ups and low coating volume, as well as safety interlocks cover the operational aspects of the machine. Details of the alarm mode and correction information are supplied to the operator via a PLC display. The automation process has greatly reduced manpower requirements. After the fiber trays are loaded the operator is free to do additional tasks, such as inspection, as the system can run unattended. An audible alarm alerts the operator to remove the fiber trays and the cycle is repeated. Consistency of operation has been the largest contributor to throughput, in addition to a 25% improvement in rejected product.

Fiber Bragg gratings recoated with this process have been tested to a 3M “Recoat Qualification Plan” (Document 78-8130-6767-1), which was derived from Telcordia GR-1221, “Generic Reliability Assurance Requirements for Passive Optical Components”.

Environmental tests included in the Recoat Qualification Plan are:

1. Hot Water Immersion
2. Tensile Test
3. Temperature Cycle
4. Cyclic Moisture Resistance
5. Damp Heat Storage
6. Thermal Shock
7. Temperature Sensitivity

Figures 9 & 10 are results of typical Weibull plots from damp heat and hot water immersion tests. The comparison of the “spray” process to a commercially available molded recoat process is represented in these graphs.

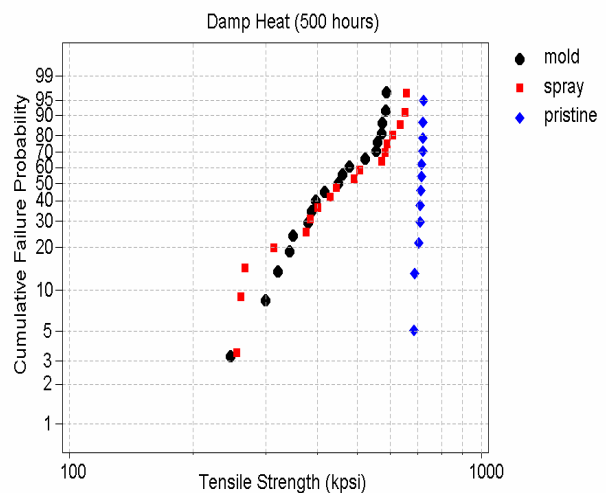


Figure 9

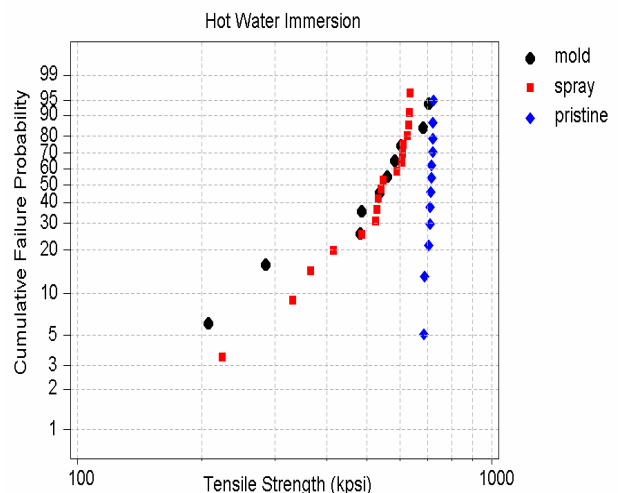


Figure 10

Reliability testing on both mold and spray recoat exposed an unexpected effect on some optical fiber types. Delamination between the coating reinstatement and glass fiber interface was observed. We were able to modify our coating chemistry to meet all of the reliability tests without delamination. We believe this is

the only chemistry and process, to date, that has resolved this undesirable delamination issue.

The thermal effects of the recoat on the fiber Bragg grating are quantified by measuring the center wavelength of the grating as a function of temperature. Figure 11 shows the temperature sensitivity of a grating with our novel recoat process compared with a non-recoated grating. The grating was written in Panda polarization maintaining fiber. The figure shows the raw data and trend lines for each data set. The non-recoated data shows thermal response of wavelength isolated to the fiber only. The two coated samples, which overlay each other, show the thermal response of wavelength for coiled and uncoiled samples. In the operating range of the device (-10°C to 80°C) the thermal response of the coated gratings (30 mm dia.) closely matches the bare glass samples.

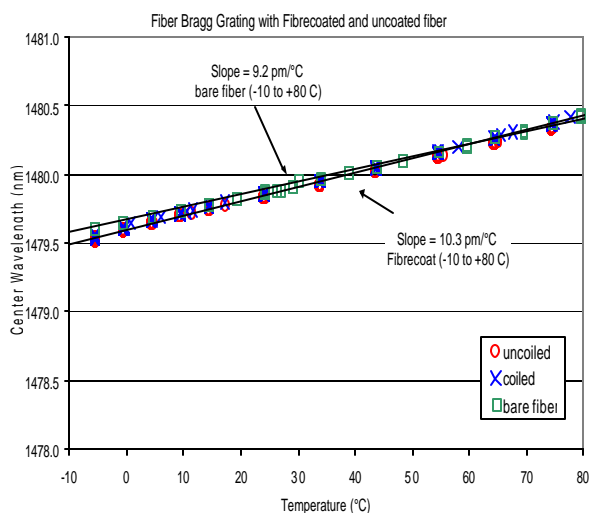


Figure 11

Conclusion

We have demonstrated a robust, high reliability semi-automated process for coating reinstatement of FGGs. Since the process is completed in free-space without molds or dies, there is little chance of the fiber contacting the device or contamination. Thus fiber strength is maintained. We are continuing work in advanced chemistry formulations for high & low temperature performance as well as other packaging opportunities. We envision use for this novel recoat capability in fusion splicing, splitter/coupler packaging & a number of other opto-electronic devices.

¹ See Crivello, CHEMTECH October 1980, pp 624-628.

² Some examples are described in US Patent 5,554,664.

³ S. R. Kerr, Adhesives Age August 1996, pp 26-34.

⁴ Chemistry & Technology of UV & EB Formulation for Coatings, Inks, & Paints, P. K. T. Oldring (Ed.) SITA Technology Ltd, Gardiner House, Broomhill Road, LONDON SW184JQ ENGLAND

⁵ Ultrasonic Liquid Atomization, Theory and Application, Harvey L. Berger, Ph.D. sonotek.com.