Tiny Triumphs: Laser Drilling Micron-Sized Holes

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Advances in medical technology require ever-smaller holes in catheters and related devices. Laser drilling achieves strict size and tolerance requirements in an economically viable process.

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The ability to produce accurate holes within tight dimensional tolerances is an important aspect of medical device design and manufacture. Numerous methods of hole production exist, with mechanical drilling, chemical etching and laser machining among the more widely used. However, as the dimension of the hole decreases, the choice of process is more limited and the interaction of the material with the hole-forming process becomes more critical. This article looks at various hole-drilling methods, and, in particular, examines the use of laser drilling techniques to make holes in diameters smaller than 20 µm. Issues involving the accurate measurement of small holes and how, as the hole size decreases, measurement becomes an increasingly complicated and critical aspect of process control, are also examined.

Define small

Traditional methods such as mechanical hole drilling allow for the creation of features on the order of 50 to 100 µm, which is roughly the diameter of a human hair. By modern standards, these holes can no longer be described as small. Refined, repeatable, high-speed laser processes can machine holes as small as 1 µm in diameter with specialised configurations, and can easily drill below the 20-µm-diameter mark in a variety of materials.

Small holes serve a number of purposes in medical devices. Tiny laser-machined holes in catheters enable drug delivery. By carefully tailoring hole density and size, the infusion of an active drug can be controlled. As technologies progress and medical devices become less invasive, it has become necessary to reduce the size of the features on these instruments, driving demand for smaller holes. The challenge lies not only in the accurate positioning of these features but in controlling hole dimensions and the materials being processed.

Small-hole production methods

Mechanical drilling involves the use of a specially designed drill bit, which rotates in contact with the workpiece to remove material and produce a circular hole. Several factors make it challenging to drill small holes using this method. First, the diameter of the drill bit must be the same size as the hole. This is difficult to achieve, and the tool is prone to break during the drilling process. Ultrahigh cutting speeds also must be used because of the drill's small size, making it difficult to eliminate vibration during the machining process. Furthermore, process repeatability can be short lived as the drill bit begins to wear. The wear issue also makes it quite difficult to drill hard materials using this manufacturing process. While mechanical drilling of holes on a larger scale is extremely economical for many materials, it is not necessarily the most feasible on the micron scale.

Punching is a commonly used method for the production of holes in thin materials. For this process, a punch and die of a specific size must be manufactured as a pair. When the material is located between the punch and die and pressure is applied, a hole is produced in the sheet by pressing out a piece of material, called a blank. This process can offer high speed, scalability and repeatability. However, punching may only be used with certain materials such as metals and polymers, and is not suitable for use with brittle ceramics. Furthermore, punching holes in sheet material is only possible if the hole diameter is greater than the material thickness. Many medical devices call for metal sheets in thicknesses of 20 µm or greater, thus making the punching of micron-sized holes impossible.

Chemical etching also can be used for the production of small features. First, the surface of the workpiece is masked off using a method such as photolithography. This involves spin coating a resin onto the surface of a workpiece, followed by exposure to UV light through a patterned projection mask. After development of the hardened resin, a mask with micron-sized features will remain, leaving the exposed parts of the pattern to undergo a chemical attack when placed in an etchant. Due to the complex process, this manufacturing method is best suited to very thin materials. Metals are frequently etched this way and ceramics also can be subjected to the process, provided suitable etchants are available. Distinct advantages of this process are the fine control, repeatability and scalability; the technique is limited, however, in terms of the materials that can be processed and the flexibility of the manufacturing method. This technique can produce holes smaller than 1 µm diameter in very thin layers. Chemical etching can be isotropic in many materials; therefore, it can be difficult to have fine control over the cross-sectional geometry of the hole.

Sandblasting, like chemical etching, can be used in conjunction with a photomask to produce features on components. This process is only suitable for use with brittle materials such as ceramics. While there are advantages to using this process for the production of larger holes, it is severely limited by the diameter of the abrasive particles used in the sandblast. This method is used to create holes down to submillimeter diameters, but it does not necessarily achieve the performance required to produce sufficiently small holes in the medical devices of today.

Electron beam machining can be used in a similar manner to laser machining to produce small holes with fine tolerances, typically in diameters as small as 25 µm. Using electrostatic lenses, the electron beam is focused to a small point, where a melt pool is generated and the material is evaporated to produce a hole. This process is limited to metals and some ceramics. Advantages include the ability to produce high-aspect-ratio holes (up to 25:1), to drill holes at an angle to the surface and to achieve a very high machining rate. This process must take place in a high vacuum, which may be an inefficient manufacturing method to include in a production line.

Electrical discharge machining (EDM) is widely used in industry for the production of small holes. While the process is restricted to conductive materials, holes down to a diameter of 5 µm can be produced repeatedly. This process involves moving a wire electrode towards the workpiece with fine current control to adjust the spark between the electrode and workpiece. The spark is the mechanism by which material is removed to create the hole. By precisely controlling the current to the electrode, it is possible to produce holes with very fine surface finishes, which makes this process popular for applications such as fuel injector nozzles. While this manufacturing method can produce holes with excellent quality, it is inferior to other processes in terms of processing speed.

Laser drilling is very common in both the medical device and electronics industries. By careful selection of a laser that is right for a given application, fine micron-sized features can be produced very economically. While capital investment may match what is required for other manufacturing methods, such as high-accuracy mechanical drilling, lasers offer unparalleled reliability and repeatability in high-speed, high-volume manufacturing environments. Somewhat similar in function to the process of electron-beam machining, the intense laser light is focused to a small point, which creates a local melt-pool where the material evaporates to produce the hole. Lasers are available with a continuous or pulsed mode of operation. Pulsed lasers allow the user to carefully control the amount of energy delivered to the workpiece, making it possible to precisely control a laser drilling process. Using specially designed optical setups it is possible to drill down to 1-µm diameters in certain thin materials, while specific drilling strategies can be employed to control the hole shape and contour.

The comparative cost of different drilling methods is shown in Figure 1. In general, the cost of producing a small hole rises exponentially as the hole diameter decreases. Laser is the one process that can be used to cover a broad range of diameters.

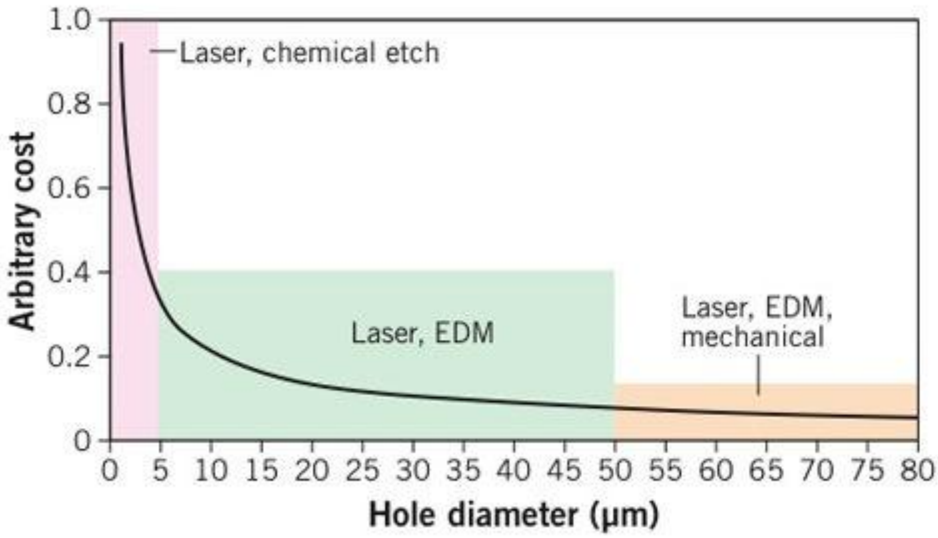

Figure 1: The cost per hole increases as the hole diameter becomes smaller. Lasers provide the greatest flexibility for manufacturing holes.

Advantages of laser drilling

Using lasers to drill small holes in medical devices has many advantages. Not only can lasers create repeatable, high-aspect-ratio holes in diameters as small as 1 µm, the noncontact process does not require additional coolants or lubricants during drilling.

The noncontact nature of laser processing is especially advantageous when machining very thin materials that are too flexible or fragile to undergo a contact machining process. With properly defined laser drilling parameters, it is possible to produce holes with a minimised heat-affected zone, thus eliminating postprocessing requirements to create a clean hole. The materials to be drilled and the size of the features required will determine the most appropriate type of laser. Typically, high-pulse-repetition rate nanosecond UV lasers operating at 355 nm are suitable for drilling most materials, as this particular wavelength of light is absorbed well by metals and polymers. Modern lasers, such as diode-pumped solid-state systems, require minimal maintenance and are very cost-effective to run, as there are virtually no short-life consumable components or tooling. Laser processing also offers flexibility in changing process parameters for different materials of varying thicknesses. Careful tuning of laser parameters such as power, pulse repetition frequency and beam speed, allows the user to control the size and cross-sectional features of any hole.

Considerations in laser drilling small holes

As previously stated, one of the main advantages of using lasers for materials processing is the possibility to choose a laser source that will achieve optimal results (Figure 2). Materials absorb different wavelengths of light in different proportions, and various applications require lasers that operate in different modes, such as pulsed or continuous wave. For very fine applications, short-pulsed lasers in the nanosecond range and below tend to provide optimal results, because heat buildup during the machining process is minimised. This, in turn, provides the possibility to machine extremely clean features without the need for postprocessing. Of course, some materials machine better than others. Polyimide and PEEK, for instance, machine particularly well with UV lasers.

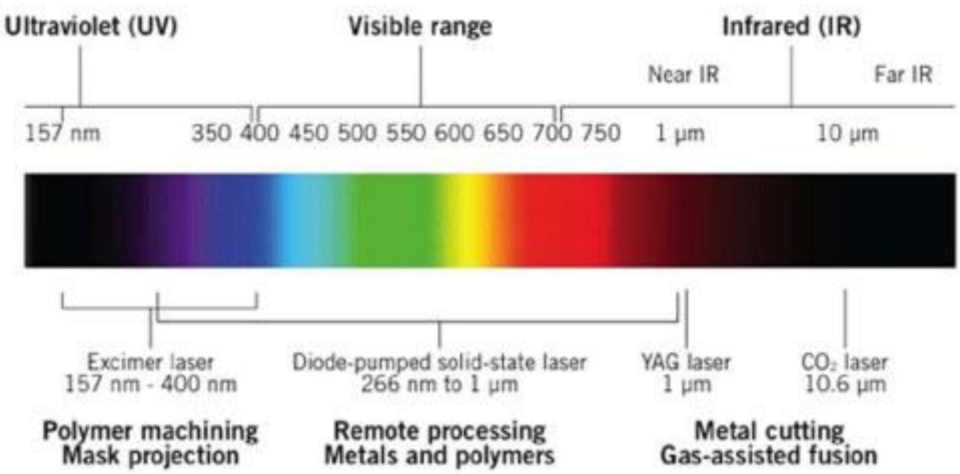

Figure 2: This graphic shows the most commonly available laser wavelengths. Wavelengths in the UV range are absorbed well by most materials, and lasers operating at 355 nm produce excellent drilling results.

When choosing a pulsed laser source, one must balance the operational characteristics of the laser—pulse frequency, pulse energy and pulse duration. While some ultrafast lasers in the pico- and femtosecond domains can machine very clean features, process time often will increase because of the lack of heat buildup in the workpiece, thus affecting the economic viability of the laser process. For many industrial processes, nanosecond pulsed lasers provide the best balance between capital investment, throughput and fine machining capabilities.

Wavelength selection is an equally important decision when designing a laser processing system. As the wavelength of the light becomes shorter, the energy of the light increases. Materials such as polymers tend to absorb UV light (with a wavelength below 400 nm) very well because of their atomic makeup and molecular bonds. Using very high energy light allows the user to perform virtual cold machining of polymers. This occurs when the light energy of the laser exceeds the potential of the molecular bonds in the material, allowing the laser light to break the bonds without generating significant amounts of heat in the workpiece. Wavelength considerations for machining metals are quite different from those for machining polymers, as the metallic bonds are normally overcome through a melt vaporisation process, meaning that heat must be introduced into the workpiece. Therefore, the actual absorption of laser light in metals is related more closely to the actual reflectivity of the workpiece to different wavelengths of light. While metals can be machined using wavelengths ranging from IR (10.6-µm CO_2 lasers) to lasers operating in the visible range (532-nm green lasers), some of the best machining of small features can be performed in the UV range (around 355 nm), as reflectivity is reduced at this wavelength. It is also imperative to choose a laser that can generate enough heat to induce melting in the machining process, such as a nanosecond laser. Hence, it is necessary to carefully consider the pulse duration and pulse energy of the laser source.

When trying to machine micron-sized features, another consideration affecting wavelength selection is that the shorter the wavelength of light, the smaller the laser's focal spot. Light is limited in focal spot size to the diffraction limit, which is dependent on the light's wavelength; hence, it is possible to have a smaller focal spot at 355 nm than at 1064 nm. This enables the user to concentrate the laser energy on a smaller area of the workpiece and thus be able to deliver energy more precisely to machine smaller and finer features. The size of the laser beam, its circularity and quality are also critical considerations when drilling very small holes, as they all influence the focal spot size.

The laser drilling strategy should also be considered. For larger holes, a common method called trepanning is used. This involves steering the beam in a spiral using scanning mirror setups. This method is suitable for drilling holes that are larger than the focal spot of the beam and for cutting square and other irregularly shaped holes.

Figure 3: The types of hole cross-sections that are feasible to manufacture using laser drilling.

When trying to drill holes at or below the focal spot size of the laser beam, it is necessary to use an alternative strategy called percussion drilling. This involves keeping the laser beam stationary, and adjusting the size and shape of the hole by carefully controlling the pulse energy, frequency and number of pulses. Figure 3 illustrates the various hole geometries that are possible by controlling the laser drilling strategy.

As holes become smaller, manufacturing costs can increase, depending on the materials machined and the tolerances required. Through the correct selection of lasers, machining strategy and materials, it is possible to optimise throughput and minimise the cost of a laser drilling process. Current diode-pumped solid state lasers have an expected minimum operational lifetime of 15,000 to 20,000 hr between services, meaning that it is feasible to run these lasers for a minimum of two to three years in full production. Because of the noncontact nature of laser machining, no consumables are used in the manufacturing process, and the inherent stability of these lasers increases repeatability, throughput and process yield.

Small-hole metrology

Traditional methods of measuring micron-sized features include high-power optical microscopy, stylus profilometry and scanning electron microscopy (SEM). While these are highly powerful characterisation tools, they are not always suited to an industrial production environment. High-power microscopy can present problems on the production line as the field-of-view is small, and the tight focal plane can complicate the measurement process. Optical microscopy is limited in resolution by the diffraction limit and therefore cannot typically resolve features below 200 nm. When used for certain applications, optical microscopy can provide a wealth of measurement information with very high repeatability and a short measurement time. This measurement technique affords the benefit of being able to measure in reflective or transmission modes, making it quite flexible across a range of materials. Special setups can be implemented when necessary to measure features in 3-D using techniques such as depth-from-focus and stereoscopy.

Stylus profilometry is also used in small-feature characterisation. Atomic force microscopy (AFM) tends to offer high resolutions on the order of nanometers, but it suffers from slow measurement speed and limited measurement range. Other stylus profilometers offer greater measurement ranges but are limited by the radius of the stylus tip (normally on the order of a couple of microns). As the stylus must make contact with each point on the measured surface in order to generate a 3-D profile, measurements can take a significant amount of extra time compared with other methods.

SEM can often provide the best measurements at the micron and nano scale. Modern SEMs can offer resolutions down to just a few nanometers and offer high accuracy and repeatability. However, this kind of microscopy is not suited to production lines as it involves a high vacuum and slow measurement times; it is normally found in R&D environments. For high-resolution measurements, nonconductive materials usually must be coated with a conductor, also making the technique less suitable for manufacturing lines in the medical device markets.

When measuring small holes, many considerations must be taken into account. First, the choice of measurement system and technique often will depend on the workpiece materials. Transparent materials are inherently difficult to characterise using optical microscopy, for example. In such cases, special techniques such as differential interference contrast must be used at greater expense and complexity than traditional brightfield microscopy. Measuring holes in semitransparent and opaque materials tends to be much simpler using the transmission brightfield technique. However, this becomes more complicated when the hole is blind. In certain cases, semitransparent materials will have an advantage when measuring a blind hole, as it is still possible to form an image with good contrast. For opaque materials, reflective brightfield microscopy often produces the best results.

Having chosen a suitable technique, the next consideration is measurement resolution and uncertainty. In a 2-D measurement in an optical system, the most important considerations should include camera resolution, illumination and distortion of the image by the optics. Modern microscope optics are optimised to minimise field distortion and colour errors and are suitable for high-accuracy measurements. The minimum measurement uncertainty should be at least half of the minimum design tolerance of the feature to be measured; thus, the minimum repeatable measurement of small holes using optical microscopy is in the region of 1 µm in most instances. For stylus measurements, it is the tip radius and shape that will define the system's minimum hole measurement capabilities.

Finally, the surrounding environment is an important consideration. Many materials will expand or contract on the order of 10 to 100 nm per Kelvin per meter. Vibration also is a key concern in a high-accuracy metrology system. By stabilising the environment in which the processes are completed and measurements are performed, smaller features can by produced with increased repeatability and process yield.

Conclusion

Current medtech manufacturing trends are driving the need to drill smaller holes with increased repeatability and process yield. While there are several suitable drilling methods, such as EDM and mechanical techniques, lasers outperform them in many applications. Because it is a noncontact process, there is less need to postprocess the drilled parts, and there is no mechanical tooling wear to consider. Lasers afford the user the possibility to drill holes smaller than can be achieved using other techniques (1 µm) while maintaining high throughput and economic viability. The metrology of small holes poses an interesting challenge, especially when considering the range of materials that can be laser drilled. Optical microscopy techniques are best suited to high-throughput manufacturing lines, while other techniques, such as electron microscopy, provide high-resolution measurements that can be used as complementary techniques, especially in an R&D environment.

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