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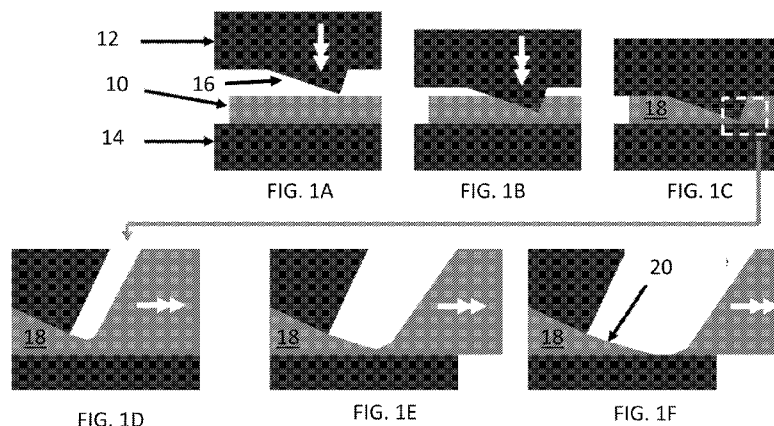
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(54) Title: **BLADE FABRICATION PROCESS AND BULK METALLIC GLASS SURGICAL GRADE BLADE**



(57) Abstract: An embodiment of the invention is a fabrication process for making a blade. The process heats bulk metallic glass to a supercooled state. While in the supercooled state, a blade is shaped in the bulk metallic glass. The blade is then drawn deforming the blade and forming a surgical grade edge on the blade. The invention can provide surgical grade blades consisting of bulk metallic glass shaped as a blade and having an edge with a radius of ~100nm or less, down to ~5nm. The blade edge transitions from localized necked material to the very small edge radius, providing a robust surgical grade blade.

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BLADE FABRICATION PROCESS AND
BULK METALLIC GLASS SURGICAL GRADE BLADE

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STATEMENT OF GOVERNMENT INTEREST

This invention was made with government support under Contract No. 0937771 awarded by National Science Foundation. The government has certain rights in the invention.

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PRIORITY CLAIM AND REFERENCE TO RELATED APPLICATION

The application claims priority under 35 U.S.C. §119 from prior provisional application serial number 61/444,864, which was filed February 21, 2011 and entitled Process for Manufacturing Edges.

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FIELD

A field of the invention is blade fabrication and surgical grade blades. Example applications of the invention include fabrication of high quality surgical blades, e.g., for ophthalmological surgery, or other blades having very small cutting edge radii.

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BACKGROUND

Diamond has been the preferred material of choice among surgeons for knife blades used in precision surgeries such as ophthalmic surgeries. Single crystal diamond provides extreme hardness and sharpness. These blades are

expensive though, and cause a typical ophthalmic surgical knife to be about \$2000-3000. See, C.H. Williamson, "Diamond knives: Are They a Clear Choice for Clear Corneal Cataract Surgery?," *Cataract and Refractive Surgery Today*, June 2007, 82-84. The diamond knife blade edges are also somewhat fragile, and require careful handling to maintain the integrity of the cutting edge.

The diamond knifed blades are also difficult to manufacture. While natural diamond is itself expensive, difficulty in manufacturing the blade cutting edge geometries, particularly the edge radius, plays a role in the expense of the diamond blade instruments. While alternative processes and materials are available, achieving high performance at a low cost is still a problem. Typical techniques for manufacturing the diamond knife cutting edge geometry include mechanical lapping, thermo-chemical lapping, chemically-assisted mechanical polishing and planarization (CAMPP) and reactive ion etching. See, I. Miyamoto, K. Kawata, M. Kimura, N. Kanekama, "Sharpening diamond knives having a small apex angle of less than 55° with high-energy argon ion beams," *Journal of Materials Science Letters*, 1988; 7(11): 1175-1177; W. J. Zong, D. Li, K. Cheng, T. Sun, H.X. Wang, Y.C. Liang, "The material removal mechanism in mechanical lapping of diamond cutting tools," *International Journal of Machine Tools and Manufacture*, 2005; 45(7-8): 783-788; W. J. Zong, D. Li, K. Cheng, T. Sun, Y.C. Liang, "The ultimate sharpness of single-crystal diamond cutting tools—Part II: A novel efficient lapping process", *International Journal of Machine Tools and Manufacture*, 2007; 47(5): 864-871; A.P. Malshe, B.S. Park, W.D. Brown, H.A. Naseem, "A review of techniques for polishing and planarizing chemically vapor-deposited (CVD) diamond films and substrates," *Diamond and Related Materials*, 1999; 8: 1198-1213. These processes are all inherently time-consuming and expensive. In addition, the manufacture of various blade geometries is complicated by the fact that surgeons require several different and at times customized angles on their diamond knife blade.

Stainless steel and silicon have also been used to make surgical blades. Stainless steel yields a much larger edge radius than diamond blades (~300 nm) due to the limitation of its crystalline structure. This results in poorer cutting performance and longer heal times. Additionally, stainless steel lacks durability to sustain its cutting edge over multiple uses. R. Angunawela, C.W. Von Mohrenfels, J. Marshall, "A New Age of Cataract Surgery," *Cataract & Refractive Surgery Today*, May 2005; 36-38. Silicon blades can reach a much smaller edge radii (~40 nm) and thus near the cutting performance of diamond. J. Albanese, G. Dugue, V. Parvu, A.M. Bajart, E. Lee, "Evaluation of a new disposable silicon limbal relaxing incision knife by experienced users," *BMC Ophthalmology*, 2009; 9:15. However, like stainless steel, they do not perform well over multiple incisions.

Peker et al. U.S. Patent No, 6,887,586 discloses a process for forming cutting tools, including surgical blades, from bulk amorphous alloys. This process relies upon a separate sharpening step that uses conventional sharpening, such as lapping, chemical machining and high energy methods. Careful handling is required for these separate sharpening steps to maintain the integrity of the edge, and reliable manufacturing of very small edge radiuses is likely difficult and expensive.

SUMMARY OF THE INVENTION

An embodiment of the invention is a fabrication process for making a blade. The process heats bulk metallic glass to a supercooled state. While in the supercooled state, a blade is shaped in the bulk metallic glass. The blade is then drawn to deform the blade and form a surgical grade edge on the blade. The process can provide a surgical grade blade consisting of bulk metallic glass shaped as a blade and having an edge with a radius of ~100nm or less. In preferred embodiments, the edge has a radius of ~5nm-100nm. The blade edge transitions

from the localized necked material to the very small edge radius produced from drawing, providing a robust surgical grade blade.

BRIEF DESCRIPTION OF THE DRAWINGS

5 FIGs. 1A-1G are schematic cross-sectional views illustrating a preferred embodiment process for fabricating a bulk metallic glass surgical grade blade of the invention;

 FIG. 2 is a schematic diagram of a micromolding system that can be used to fabricate bulk metallic glass surgical grade blades;

10 FIGs. 3-5 show the load cell force data from multiple fabrication tests at three different temperatures (650K, 660K, 670K) for demonstrating the method of FIGs. 1A-1G;

 FIGs. 6A-6P are SEM images of a blade and blade edges formed during experiments;

15 FIG. 7 shows a plot of temperature versus feedrate for all tests with the results qualitatively assessed to be either good or poor;

 FIG. 8A illustrates different deformation modes as a function of strain rate and temperature for the bulk metallic glass $\text{Zr}_{41.25}\text{Ti}_{13.75}\text{Cu}_{12.5}\text{Ni}_{10}\text{Be}_{22.5}$, which was used in experiments to form blade edges; FIG. 8 B illustrates peak
20 force versus feed rate for temperatures of 650K, 660K and 670K; and FIG. 8C illustrates drawing distance versus federate at the three different temperatures;

 FIG. 9 illustrates the type of deformation occurring for 660K and 100 $\mu\text{m/s}$ as a function of force and drawing distance;

 FIGs. 10A-10D are example images from the video of the 660 K and
25 100 $\mu\text{m/s}$ test at selected drawing distances that were used to obtain the data in FIG. 9;

 FIG. 11 illustrates the type of deformation occurring for 660K and 1000 $\mu\text{m/s}$ as a function of force and drawing distance;

FIGs. 12A-12D are example images from the video of the 660 K and 1000 $\mu\text{m/s}$ test at selected drawing distances that were used to obtain the data in FIG. 11;

FIG. 13 illustrates the type of deformation occurring for 670K and 750 $\mu\text{m/s}$ as a function of force and drawing distance;

FIGs. 14A-14E are example images from the video of the 670 K and 750 $\mu\text{m/s}$ test at selected drawing distances that were used to obtain the data in FIG. 13;

FIGs. 15A-15D show a selection of various edges formed under different temperatures and with different deformation rates (670K, 500 $\mu\text{m/s}$; 650K, 500 $\mu\text{m/s}$; 660K, 750 $\mu\text{m/s}$; and 670K, 1000 $\mu\text{m/s}$; respectively) showing the different types of failures; and

FIGs. 16A and 16B are images of an example blade that was machined to reveal a cross section.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The invention provides a method for making high quality blades in bulk metallic glass. A supercooled material state is used to form a blade, e.g., via micromolding in a die. The initial forming process can form blades of generally arbitrary shape. Different rake angles can be formed. The blade is then drawn to form an edge. Edge radiuses below $\sim 100\text{nm}$ can be formed, including edges in the range of $\sim 5\text{-}100\text{nm}$. Edges are suitable for surgeries, such as ophthalmological surgeries. Advantageously, the bulk metallic glass blades formed in the invention are less expensive than state of the art diamond blades used for such surgeries as well as for other applications. In addition, the bulk metallic glass is biocompatible.

A preferred process for manufacturing bulk metallic glass surgical blades uses thermally-assisted molding and drawing. The shape and edge of the

blade is created in a single simultaneous process that starts with blanks of bulk metallic glass, e.g., being rectangular in shape and of specific dimensions. A high force precision mold is then used to form a rake face of the blade until only a small thickness of material remains at the edge. The remaining thickness is then drawn causing necking of the material until failure occurs along a fine edge.

Preferred processes of the invention can efficiently and economically manufacture surgical-grade blades. The resulting bulk metallic glass blades have superior properties and higher performance than current metal alloys at a price point significantly lower than precision diamond blades.

In a preferred process of the invention, an entire blade or plurality of blades are manufactured in a single two-stage process. This limits the handling of delicate pieces and chance for contamination along with increasing efficiency. The process is very fast, requiring less than a minute to completely mold and draw the blade. Additionally, no timely post-processing like lapping is required to produce the final edge, saving time and money. Several parameters (blade thickness, molding depth, temperature and draw rate) can be easily adjusted to accommodate different metallic glasses or fine tune edge formation.

Preferred embodiments of the invention will now be discussed with respect to the drawings. The drawings may include schematic representations, which will be understood by artisans in view of the general knowledge in the art and the description that follows. Features may be exaggerated in the drawings for emphasis, and features may not be to scale.

FIGs. 1A-1G illustrate a preferred embodiment process for fabricating a bulk metallic glass surgical grade blade of the invention. A bulk metal glass sample 10 in FIG. 1A has been heated to a supercooled temperature. The heating can be accomplished through contact with an upper 12 and or lower die 14 or via other heating techniques such as environmental heating in a furnace chamber, resistive heating with electrical current, and immersion in liquid. The heating through die contact may create desirable temperature gradients in material

and is also preferred as a simple and inexpensive way to implement the preferred process. One or both of the dies 12, 14 include a mold 16 for shaping a blade from the bulk metallic glass 10 while it is maintained in the supercooled state. Bringing the dies together such as by vertical movement of the upper die 12 provides an
5 initial blade shape 18 in FIGs. 1B and 1C. While the cross-section shows a single blade portion, the mold 16 obviously can be configured to form a plurality of blades simultaneously. In FIGs. 1D-1F, the blade 18 is drawn to deform the blade 18 and form a surgical grade edge 20 on the blade. This can be accomplished by moving the bulk metallic glass sample 10 in the horizontal
10 direction as shown. Once the drawing is completed, the dies are moved apart from each other to release the final, finished blade, which does not require further processing or sharpening to form the desired edge radius

The process is capable of blades suitable for applications requiring the finest blade edge. Experiments have demonstrated edges with a 14-100nm
15 radius, and the experiments indicate that a 5nm radius edge can be achieved with optimization. An endless variety of sizes and shapes can also be produced. Typical blades of interest for surgical and scientific applications range from about 1-4mm wide, 4-10 mm long and 200-500 μm thick. The shape, number of edges and angles can vary significantly between blade designs and the molding process
20 can produce the necessary geometry for mounting to the blade to a handle either during the edge forming process or earlier when producing the initial material blanks prior to edge forming.

In preferred embodiments, the bulk metallic glass 10 is a zirconium-based bulk metallic glass. Bulk metallic glasses transition to a supercooled liquid
25 state at high temperatures. This supercooled state allows the use of the present fabrication process with thermally-assisted shaping and drawing.

A preferred bulk metallic glass includes compositions having Zr, Ti, Cu, Ni, and Be, e.g., $\text{Zr}_{41.25}\text{Ti}_{13.75}\text{Cu}_{12.5}\text{Ni}_{10}\text{Be}_{22.5}$, which is available commercially under a brand called Vitreloy-1. The onset of glass transition for

$\text{Zr}_{41.25}\text{Ti}_{13.75}\text{Cu}_{12.5}\text{Ni}_{10}\text{Be}_{22.5}$ has been previously determined to at 625K. However, significant softening of the material does not occur until around 650K. The material has a relatively large stable supercooled region of about 80K where it follows a time/temperature-dependent relation to crystallization, which makes it very suitable for the present fabrication process. During this time, the structure of the material slowly reverts to its stable structure through crystal growth. At or above 705 K crystallization is unavoidable. Detailed material properties are given in J. Lu, G. Ravichandran, W.L. Johnson, "Deformation behavior of the $\text{Zr}_{41.25}\text{Ti}_{13.75}\text{Cu}_{12.5}\text{Ni}_{10}\text{Be}_{22.5}$ bulk metallic glass over a wide range of strain-rates and temperatures", *Acta Materialia*, 2003; 51(12): 3429-3443. Advantageously, this bulk metallic glass has a relatively broad supercooled range. It is categorized as an amorphous alloy or bulk metallic glass due to its chemical makeup and atomic structure. Rapid cooling (1 K/s) during solidification from a melt allows the glass to reach a metastable condition in which the amorphous structure that existed in its liquid state is maintained, and it has a lower critical cooling rate to maintain its amorphous structure than most metallic glasses. It has an amorphous structure, high strength (1900 MPa) and high hardness (534 HV). The strength and hardness are equivalent to standard tool steels and are ideal for the formation and retention of a sharp edge. It reaches 2% elongation before failure at room temperature, which is greater than similar high strength brittle metals and ceramics. Additionally, Zirconium-based alloys have been shown to be fully biocompatible and unlike many plastic and silicon instruments, can be sterilized with any current medical method. See, L. Liu, C.L. Qiu, C.Y. Huang, Y. Yu, H. Huang, S.M. Zhang, "Biocompatibility of Ni-free Zr-based bulk metallic glasses," *Intermetallics*, 2008; 17(4): 235-240; J.A. Horton, D.E. Parsell, "Biomedical Potential of a Zirconium-Based Bulk Metallic Glass," *Materials Research Society*, 1999; 754: 179-184.

There are a wide variety of known bulk metallic glasses that artisans will recognize as viable for use in the present process. Zirconium based bulk

metallic glasses especially those similar to the example compositions are widely available and well understood. The properties identified by the inventors for the current process can guide artisans in the selection of other suitable bulk metallic glasses.

5 The drawing in FIGs. 1A-1F is preferably conducted at a rate and a supercooled temperature that initially produces elastic deformation followed by plastic deformation with localized necking. Explained further with respect to experiments below, high temperatures in the supercooled range of the bulk metallic glass produce the desirable formation with higher drawing speeds, while
10 lower temperatures in the supercooled regions work with lower drawing speeds. Optimizations for an example material are discussed below with respect to experiments.

FIG. 2 shows a micromolding system for forming bulk metallic glass surgical grade blades with the FIGs. 1A-1F process. Items identified in FIGs. 1A-
15 1F are given the same reference numbers in FIG. 2. Two microactuators 22, 24 control the shaping and drawing processes. The microactuators 22, 24 can be controlled by a computer program carried out by a microcontroller for molding and drawing a particular blade shape and bulk metallic glass material being processed. The mold 16 is shown as a pair of die inserts. Die heaters 26 and 28
20 are embedded in the dies 12 and 14 and can likewise be controlled by a microcontroller that is programmed to carry out a particular molding and drawing operation with a given temperature and speed profile. The bulk metallic glass sample 10 is held by an adaptor plate 30 attached to a load cell 32. The load cell can be used to monitor force and as a check by a controller running a fabrication.

25 Experiments demonstrated the fabrication process of the invention and produced example blades of the invention. The experimental details will provide guidance for techniques to use other bulk metallic glasses and for the optimization of fabrication processes, as well as providing additional details regarding features of the above discussed embodiments.

Experimental Details

A system consistent with FIG. 2 was used in experiments. The upper die was controlled by a ball screw actuator capable of outputting over 1000N of force. An LVDT (Linear Variable Differential Transformer system) provided feedback to a process controller that was used to measure the gap between the upper and lower die with a resolution of 100nm. An additional actuator with sub-micron precision was used to draw the sample horizontally. The critical geometries of both the upper and lower dies utilize tool steel mold inserts for maximum strength, higher precision and easy maintenance. The lower die was adjustable to allow precise alignment of the upper and lower dies to create a uniform gap thickness during molding. The upper die was designed to produce a 20° rake angle in the final blade. Heating is accomplished through resistive cartridge heaters placed within the upper and lower dies. Thermocouples are placed close to the die inserts to provide accurate temperature measurement. Temperature was regulated using a multi-channel PID controller providing an accuracy of $\pm 1\text{K}$. The testbed was CNC-controlled.

Tests were conducted by clamping a sample in the adapter plate on the horizontal actuator. Next, the heating is activated and allowed to stabilize at the required operating temperature. At this point the CNC program is activated, which proceeds by first zeroing the upper die through contact to calibrate the LVDT. The actuator then moves the sample into the dies and pauses until the sample reaches the pre-specified operating temperature. Then the shaping and drawing are conducted as discussed above while the temperature is maintained at the predetermined temperature in the supercooled range.

Experiments were conducted across five drawing feedrates (100, 250, 500, 750, and 1000 $\mu\text{m/s}$) and three temperatures (650, 660 and 670K) to study the deformation of $\text{Zr}_{41.25}\text{Ti}_{13.75}\text{Cu}_{12.5}\text{Ni}_{10}\text{Be}_{22.5}$ samples within its supercooled region as well as to determine the best conditions for edge formation.

Based on preliminary experiments over a wider range, the above feedrates were chosen to study deformation relevant to edge formation. Tests above 670K could not be reliably performed without crystallization and at tests below 650K the material approaches the behavior of a standard metal, which is not desirable for the present process.

The samples were 40 mm x 2 mm x 500 μ m (LxWxH). Multiple tests were run along the length of this sample, each test producing final blades roughly 3mm x 2mm x 500 μ m. The upper die was stopped at a gap thickness of 20 μ m for all tests. Using a 500N load cell, drawing force data was recorded to quantitatively analyze the deformation occurring in the sample. Additionally, a camera with a 200X microscope lens was used to provide a video record of each test in order to help visualize the deformation occurring during the test.

FIGs. 3-5 show the load cell force data from each test at the three different temperatures (650K, 660K, 670K). The force is plotted versus the drawing distance. Drawing distance is used to represent strain in the sample, since exact elongation was difficult to measure. The varying response across each parameter is due to the combined strain rate and temperature dependence of bulk metallic glass within its supercooled region. The material exhibits higher strength at both lower temperatures and higher feedrates. As feedrate increases, the peak force for all the temperatures increases, but the drawing distance until failure quickly decreases. Additionally, as the feedrate increases the shape of the plot shifts from an almost flat line, to a gradual drop off, to eventually a quick rise and fall at the highest feedrates and lowest temperatures. Due to the dependence of the material properties on both temperature and strain rate, it is possible to realize similar force responses at different combinations of temperatures and feedrates, e.g., compare the plot of 500 μ m/s at 660K, with 100 μ m/s at 650K.

FIGs. 6A-6P are SEM images of a blade and blade edges formed during experiments. FIG. 6A shows a complete blade. FIGs. 6B-6P show the blade region highlighted in FIG. 6A. FIG. 6B-6P have edges formed at different

temperatures in Kelvin and feed rates in $\mu\text{m/s}$, and dotted lines indicate the point at which deformation began as a result of drawing. The respective temperatures and feed rates were: FIG. 6B - 650/100; FIG. 6C - 650/250; FIG. 6D - 650/500; FIG. 6E - 650/750; FIG. 6F - 650/1000; FIG. 6G - 660/100; FIG. 6H - 660/250; FIG. 6I - 650/500; FIG. 6J - 660/750; FIG. 6K - 660/1000; FIG. 6L - 670/100; FIG. 6M - 670/250; FIG. 6N - 670/500; FIG. 6O - 670/750; FIG. 6P - 670/1000.

The test at 650K and a feedrate of 1000 $\mu\text{m/s}$ (650/1000, FIG. 6F), shows one extreme where the material barely deforms before failing, exhibiting very rapid necking and only a small amount ($<20\mu\text{m}$) of elongation before failing along a jagged edge. At the other extreme (670/100, Fig. 6L), a large amount of elongation occurs (600 μm) creating a weak, flimsy edge of very thin cross section ($<1\mu\text{m}$). Although the final edge may be of small radius, the blade structure directly behind the cutting edge is deemed insufficient to support the edge during cutting. Between these two extremes there is a balance between necking and elongation that produces a stable edge of small radius, e.g. FIGs. 6B, 6C, 6I, 6J, 6P.

FIG. 7 shows a plot of temperature versus feedrate for all tests with the results qualitatively assessed to be either good or poor. There appears to be a decidedly linear relation that defines the loci of temperature and feedrate combinations that produce good edges.

The particular bulk metallic glass in the experiments was found to follow several deformation models depending on the temperature and strain rate, as seen in FIG. 8A. When within the Newtonian zone, the material follows the model of a Newtonian fluid with a relatively constant viscosity, viz., strain rate is directly proportional to stress. With an increase in strain rate or decrease in temperature, the material begins to shift to non-Newtonian behavior. This results in a viscosity that varies with strain rate rather than remaining constant. Further increases in strain rate or decreases in temperature cause a shift to shear

localization. This inhomogeneous deformation is characterized by the formation of localized shear bands and fracture of the material.

FIG. 8B shows a consistent trend of increasing force with either an increase in feedrate or a decrease in temperature. This follows the expected behavior of a Newtonian fluid. The increase in force with feedrate is fairly linear across each temperature, except at 650K where the graph is slightly concave. This represents a shift towards non-Newtonian deformation and a decrease in viscosity with increasing strain rate. In addition to the change in force behavior, this shift towards non-Newtonian deformation has adverse effects on edge formation. This can be seen in FIGs. 6D-6F, where decreasing viscosity and a shift towards inhomogeneous deformation result in poor edge formation. The material does not have sufficient time for structural relaxation to keep up with the rate of deformation. The change in peak force versus temperature at a given feedrate is not linear, with a larger increase in force between 660 and 650 K, due to the non-linear relationship between viscosity and temperature.

FIG. 8C shows that the drawing distance is roughly bounded by 140 μm on the low end due to elastic deformation in the bulk of the sample for the tests at 660 K and 670 K. FIG. 6F shows that the plastic deformation only occurs over about 30 μm (the distance from the dashed line to the left edge). The highest elongation was seen at 650 K and a feedrate of 100 $\mu\text{m/s}$ where the material failed at a drawing distance of 1500 μm . This is the extent to which the material can draw before the thickness becomes too thin and unstable. From FIG. 7 it appears that the best results occur at combinations of low temperatures and low feedrates as well as high temperatures and high feedrates. This corresponds to forces and elongations in FIGs. 8B and 8C, respectively, in the intermediate ranges of 25-55N and 230 – 670 μm .

Video from each test was synchronized with the drawing distance to characterize each stage of deformation and thereby better understand the deformation occurring. Three distinct types of edge formation were seen and can

be exemplified by the tests at 660 K and a feedrate of 100 $\mu\text{m/s}$, 660 K and a feedrate of 1000 $\mu\text{m/s}$, and 670 K and a feedrate of 750 $\mu\text{m/s}$. They are elastic deformation, plastic deformation with no cross section reduction and plastic deformation with localized necking. During elastic deformation, the sample undergoes elastic elongation across its entire length. Plastic deformation with no cross section reduction is a result of the formation of a stable neck during the drawing of material. At this time the thickness of the material in the necked region does not significantly change, but large amounts of elongation can occur. During plastic deformation with localized necking, the material only deforms at the point of thinnest cross section and continues to reduce in area until failure.

FIG. 9 illustrates the type of deformation occurring for 660K and 100 $\mu\text{m/s}$ as a function of force and drawing distance, and it is seen that there is a very small section of elastic deformation. Once a certain peak force is reached, the material begins to plastically deform over a large region ($\sim 800 \mu\text{m}$) with very little reduction in cross section. After significant elongation has occurred the material eventually undergoes localized necking followed by failure (See FIGs. 6G, 6H, 6L, 6M, 6N).

FIGs. 10A-10D are example images from the video of the 660 K and 100 $\mu\text{m/s}$ test at select drawing that was used to obtain the data in FIG. 9. The first 100 μm consist of elastic deformation indicated by the very small amount of change seen between FIGs. 10A and 10B. Between 100 μm and 900 μm the material elongates significantly with very little reduction in cross section, as seen in FIGs. 10C and 10D. Peak forces for this case are less than 25N and elongations are greater than 600 μm . This case corresponds to the upper left hand corner of FIG. 7.

Plastic deformation with a constant cross section occurs in the necked region due to strain hardening in the material during deformation. This hardening allows the formation of a stable neck causing further deformation to take place beyond the necked region and extend over a greater length. This strain

hardening is an effect generally caused by either crystalline structure or polymer chains in other materials, both of which are absent in bulk metallic glasses. The strain hardening in this case is caused by nano-crystallization in the material during testing. In previous deformation studies, nano-crystallization was seen to occur if the material was held at a given temperature above the glass transition for an extended period of time. See, Q. Wang, S. Gravier, J.J. Blandin, J.M. Pelletier, J. Lud, "Deformation and crystallization of a $\text{Zr}_{41.2}\text{Ti}_{13.8}\text{Cu}_{12.5}\text{Ni}_{10}\text{Be}_{22.5}$ bulk metallic glass in the supercooled liquid region," *Materials Science and Engineering A*, 2006; 435–436:405–411. This nano-crystallization was then shown to increase the strength and hardness of the material. However, in this case the material only stays within the glass temperature region for a fairly short period of time. Wang et al. has shown, through high speed hot rolling, that high deformation rates and large amounts of deformation can also cause nano-crystallization, increasing material strength and hardness. G. Wang, S. Fang, X. Xiao, Q. Hua, J. Gu, Y. Dong, "Microstructure and properties of $\text{Zr}_{65}\text{Al}_{10}\text{Ni}_{10}\text{Cu}_{15}$ amorphous plates rolled in the supercooled liquid region," *Materials Science and Engineering A*, 2004; 373:217–220. This same effect is believed to cause the strain hardening seen during the tests conducted herein.

For the cases where the temperatures are low and the feedrates are high, e.g., 660K and 1000 $\mu\text{m/s}$ (FIG. 11), plastic deformation occurs very rapidly due to only localized necking. This can be seen best in the SEM image of the test sample (FIG. 6K) where there is sharp necking over a small amount of deformation before failure. Due to the high rate of necking, tests that follow this style of deformation tend to fail in a manner that creates a jagged uneven edge (See FIGs. 6D, 6E, 6F, 6k). Comparing the images acquired from video (FIGs. 12A-12D), the difference between 0 and 100 μm shows little plastic deformation as expected, while the continued drawing over the next 100 μm results in rapid necking and failure. Peak forces for these cases are greater than 50N and

elongations prior to failure are less than a drawing distance of 170 μm . These tests correspond to the lower right hand corner of FIG. 7.

For the cases where both the temperatures and feedrates are either high or low, e.g., 670K and 750 $\mu\text{m/s}$ (FIG. 13), there is a similar sequence of events to that seen in FIG. 9. However, the amount of constant cross section plastic deformation is significantly less than that seen at higher temperatures and lower feedrates. After the initial elastic deformation, there is a slight amount of plastic deformation that is then followed by localized necking, which dominates the deformation in this case. This localized necking exhibits small amounts of strain hardening causing it to reduce at a slower rate than that seen in FIG. 11. This type of deformation is ideal for blade formation since it strikes a balance between constant cross section elongation and necking (See FIGs. 6B, 6C, 6I, 6J, 6O, 6P). The sequence in FIGs. 14A-14E of 670K and 750 $\mu\text{m/s}$ confirms this deformation by showing very little movement between 0 and 45 μm followed by plastic deformation and localized necking at 200 and 400 μm , respectively. Tests near the line in FIG. 7 exhibit this type of deformation. Peak forces and drawing distances are again in the intermediate ranges of 25-55N and 230 – 670 μm . These forces and elongations are highly dependent on the blade width and starting thickness. In the experiments, the width and thickness were respectively 2mm and 20 μm . The nano-crystallization in this case is useful for edge formation because it helps control the rate of necking and thus allows the formation of a stable edge.

Edge radius and edge failure were analyzed through a combination of SEM imaging and focused ion beam machining. A JEOL 6060LV SEM was again used to take images of the blade edge to estimate the edge radius and uniformity. FIGs. 15A-15D show a selection of various edges formed under different temperatures and with different deformation rates showing the different types of failures. FIG. 15A shows the edge formed after the type of deformation seen in FIG. 9. The edge is fairly uniform and homogeneous up until the failure, but the material is very thin and doesn't have a significant rake angle for stability.

FIG. 15B shows the edge formed after the deformation seen in FIG. 11. In this case, the necking and failure occurs so rapidly that little time is allowed for the material to homogeneously neck and deform to a single edge. As the material rapidly necks to thinner cross sections, it begins to fail in a somewhat irregular fashion, creating a jagged edge. FIGs. 15C and 15D show edges formed from deformation similar to that in FIG. 13. In these cases, deformation follows a rate of necking that gives rise to the formation of a strong stable edge. However, the edge in FIG. 15D deformed more homogeneously before failure creating a more consistent and sharper edge than that of FIG. 15C, owing to the increase in temperature and feedrate.

An FEI Dual Beam 235 FIB was used to perform focused ion beam machining on the sample shown in FIG. 15D to further analyze the edge radius. The sample was initially coated with Au to prevent damage to the edge during ion milling, as well as, provide more contrast when viewed under SEM. Inside the FIB, the sample was then coated with Pt to further protect the edge during machining. Next, ion milling was used to cut a slot into the edge in order to view a cross section of the tip. FIGs. 16A and 16B show the darker color within the dashed lines that represents the bulk metallic glass while the lighter portion is the Pt coating. From this image the edge radius can be estimated to be about 50 nm for this particular sample. Additional experiments guided by these results refined the edge radius to 14nm, and the experiments suggest that under the ideal conditions, the method could produce edges having a 5nm edge radius.

While specific embodiments of the present invention have been shown and described, it should be understood that other modifications, substitutions and alternatives are apparent to one of ordinary skill in the art. Such modifications, substitutions and alternatives can be made without departing from the spirit and scope of the invention, which should be determined from the appended claims.

Various features of the invention are set forth in the appended claims.

CLAIMS

1. A fabrication process for making a blade, comprising:
heating bulk metallic glass to a supercooled state;
shaping a blade from the bulk metallic glass while it is maintained in
5 the supercooled state; and
drawing the blade to deform the blade and form a surgical grade
edge on the blade.
2. The method of claim 1, wherein said drawing is conducted at
10 a rate and a supercooled temperature that initially produces elastic deformation
followed by plastic deformation with localized necking.
3. The method of claim 1, wherein said shaping comprises
molding.
15
4. The method of claim 3, wherein said molding comprises
pressing a microcontrolled die mold into said bulk metallic glass in first direction
and said drawing comprises pulling the blade with a microactuator in a second
direction that is perpendicular to the first direction.
20
5. The method of claim 1, wherein said bulk metallic glass
comprises a zirconium-based bulk metallic glass.
6. The method of claim 5, wherein said bulk metallic glass
25 comprises $\text{Zr}_{41.25}\text{Ti}_{13.75}\text{Cu}_{12.5}\text{Ni}_{10}\text{Be}_{22.5}$.
7. The method of claim 6, wherein said drawing is conducted
with forces in the range of 25-55N to produce an elongation in the range of 230 –

670 μm and while maintaining a supercooled temperature in the range of 650-670K.

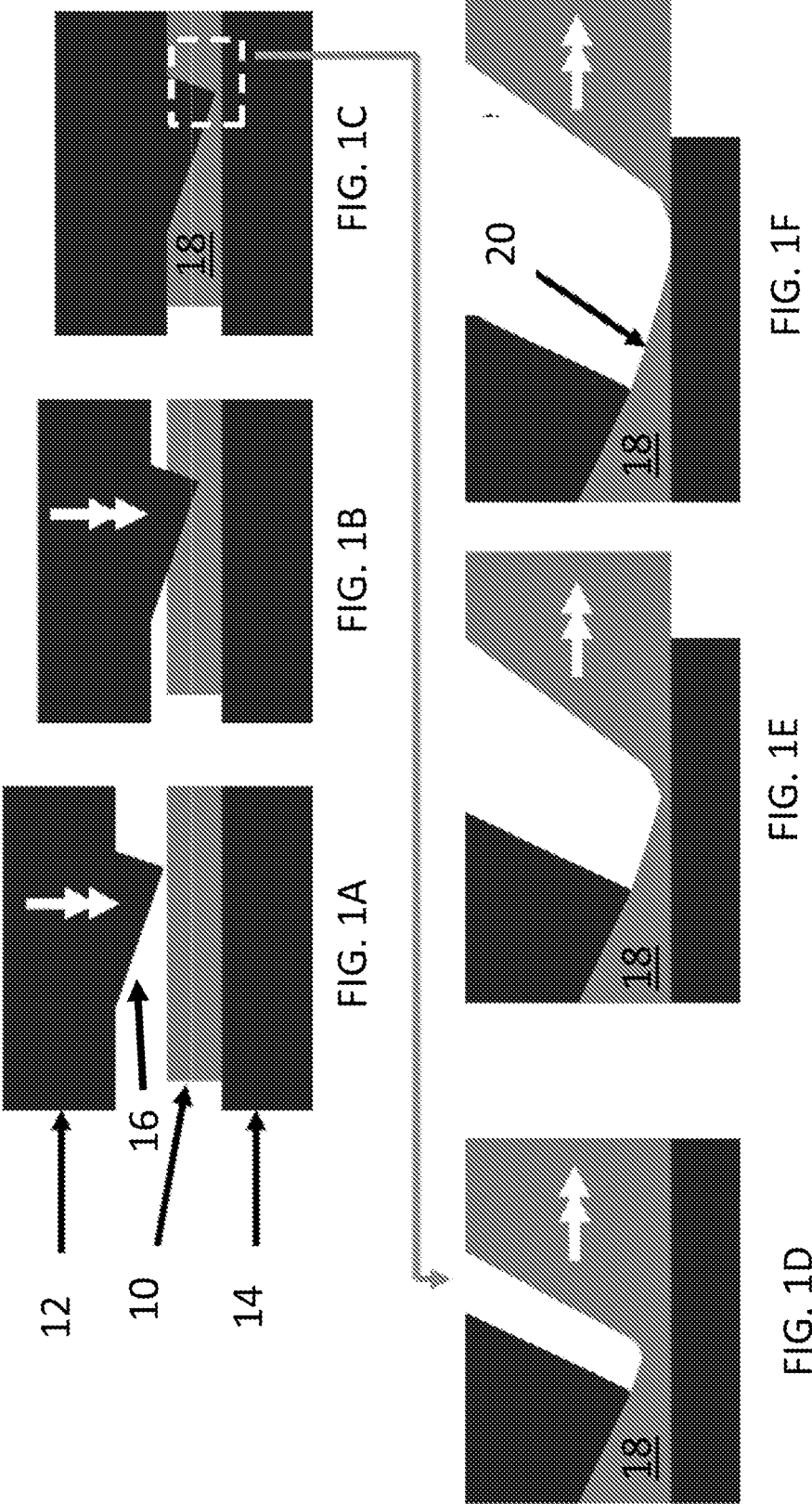
8. The method of claim 1, wherein said drawing is conducted
5 with forces in the range of 25-55N to produce an elongation in the range of 230 – 670 μm and while maintaining the supercooled state

9. A surgical grade blade consisting of bulk metallic glass
shaped as a blade and having an edge that begins with a transition of localized
10 necked bulk metallic glass material and terminates with an edge radius of $\sim 100\text{nm}$ or less.

10. The blade of claim 9, wherein said edge radius is $\sim 5\text{-}100\text{nm}$.

11. The blade of claim 10, wherein the blade is in the range of 1-
15 4mm wide, 4-10 mm long and 200-500 μm thick.

12. The blade of claim 10, wherein bulk metallic glass comprises
a zirconium-based bulk metallic glass.



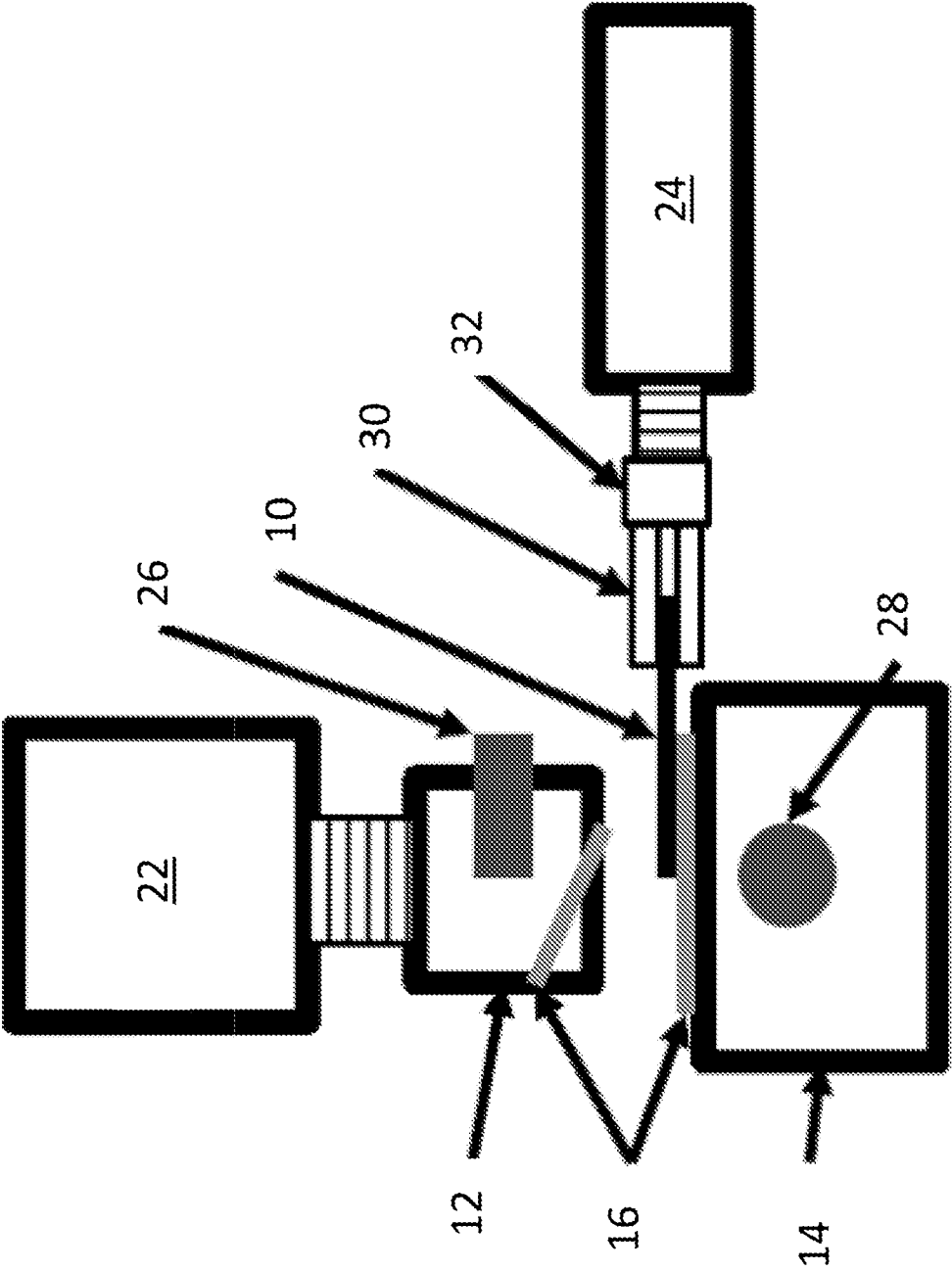


FIG. 2

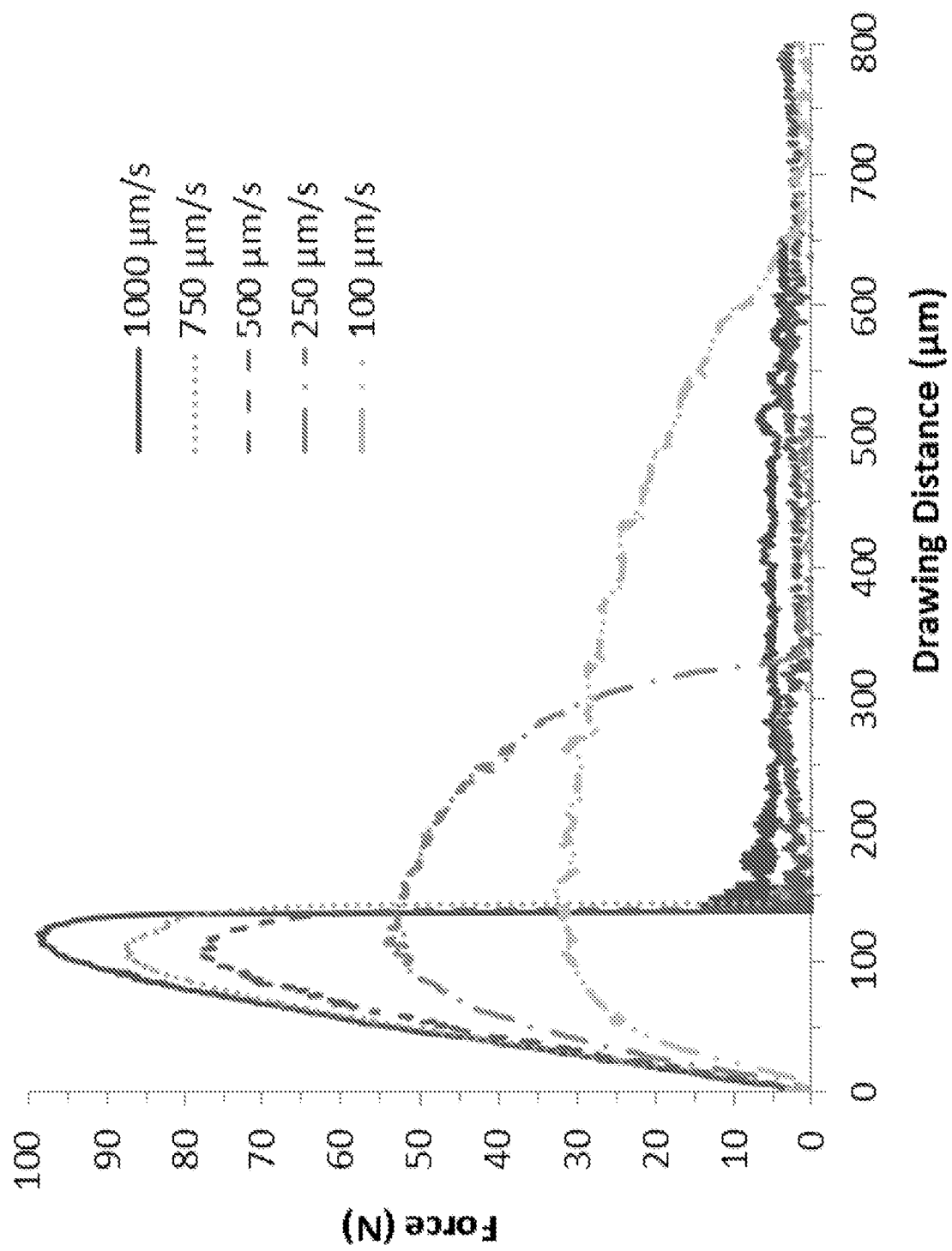


FIG. 3

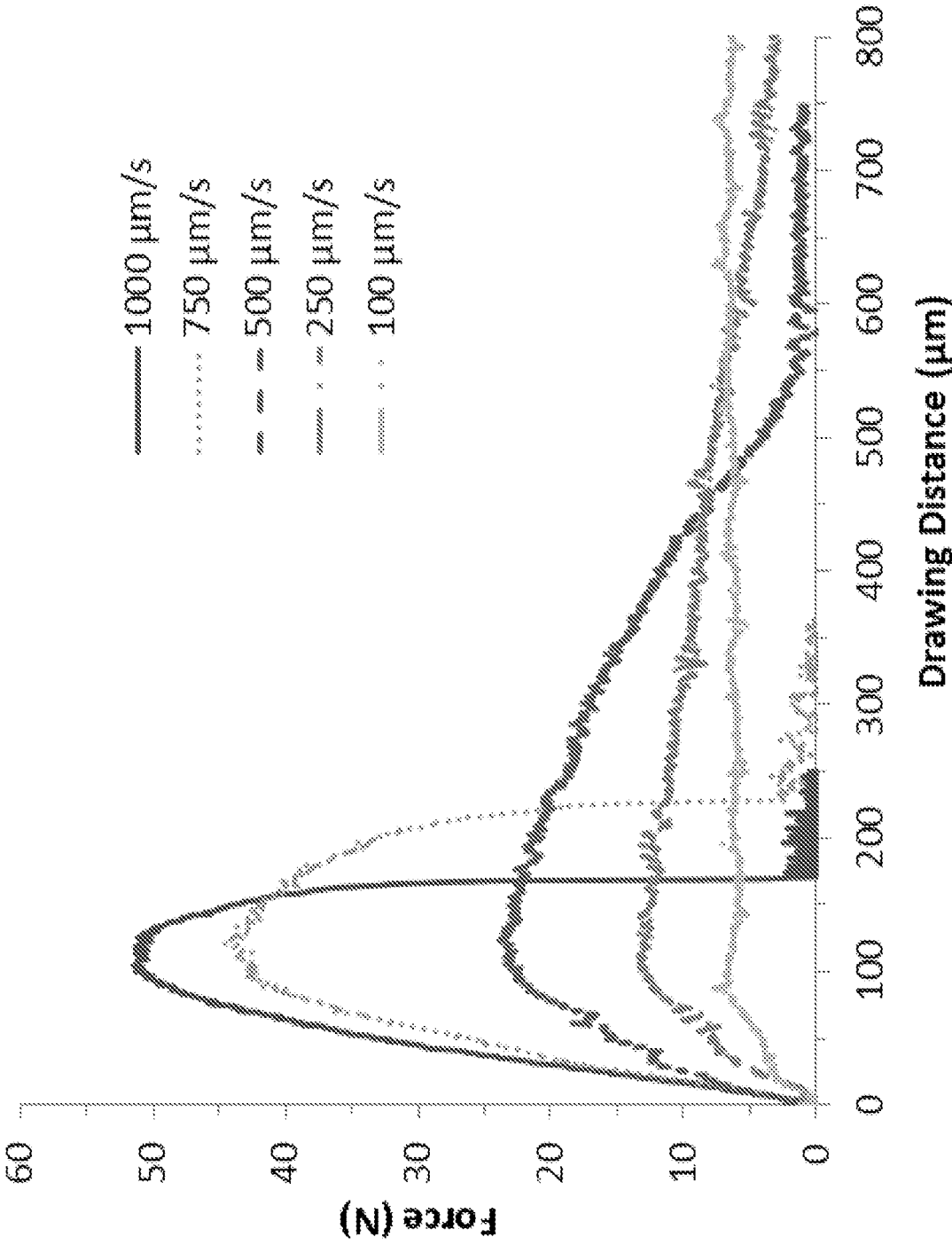


FIG. 4

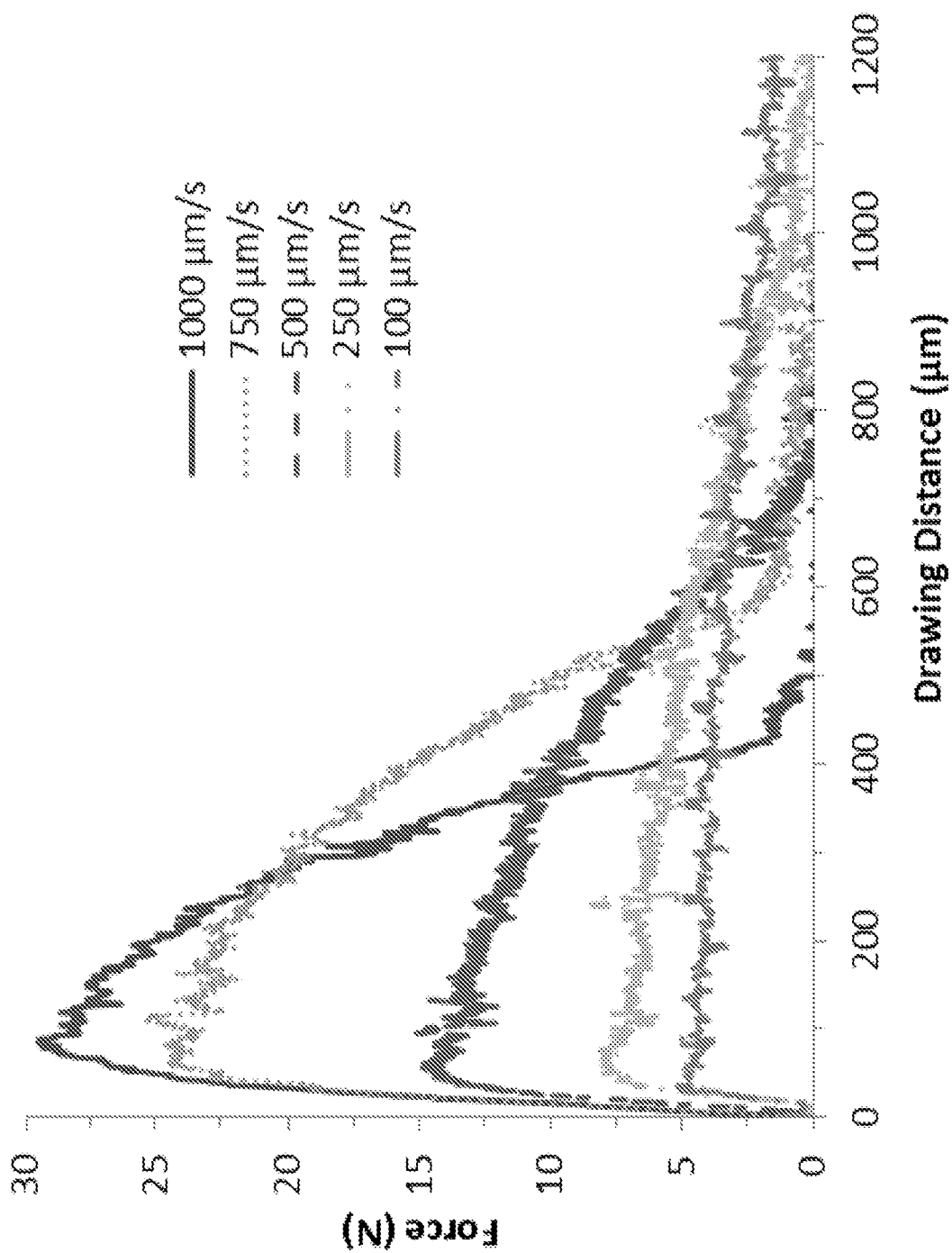


FIG. 5

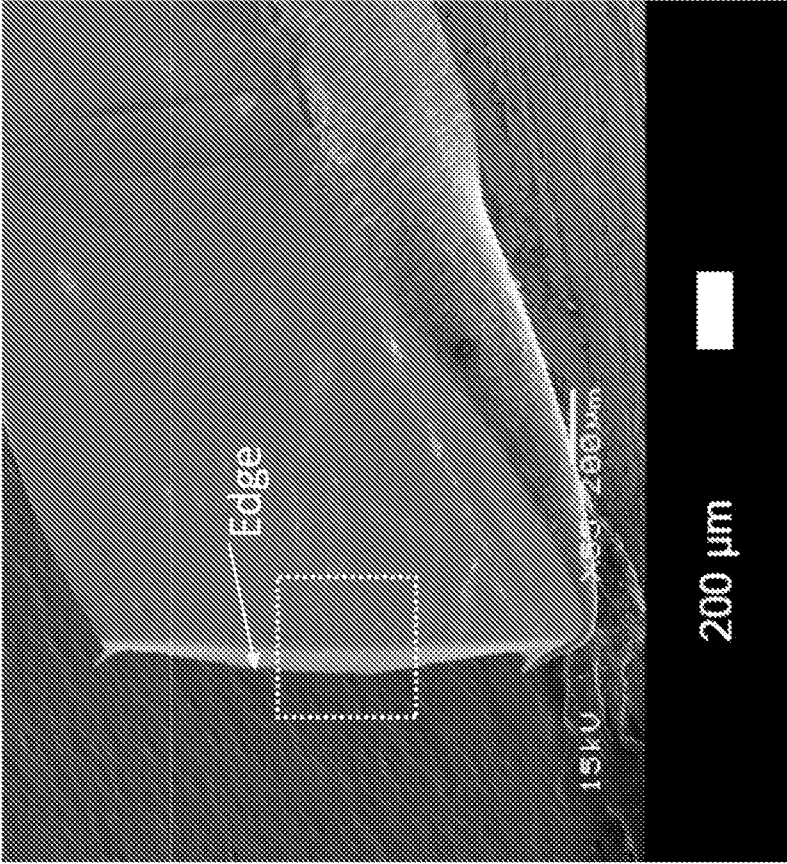


FIG. 6A

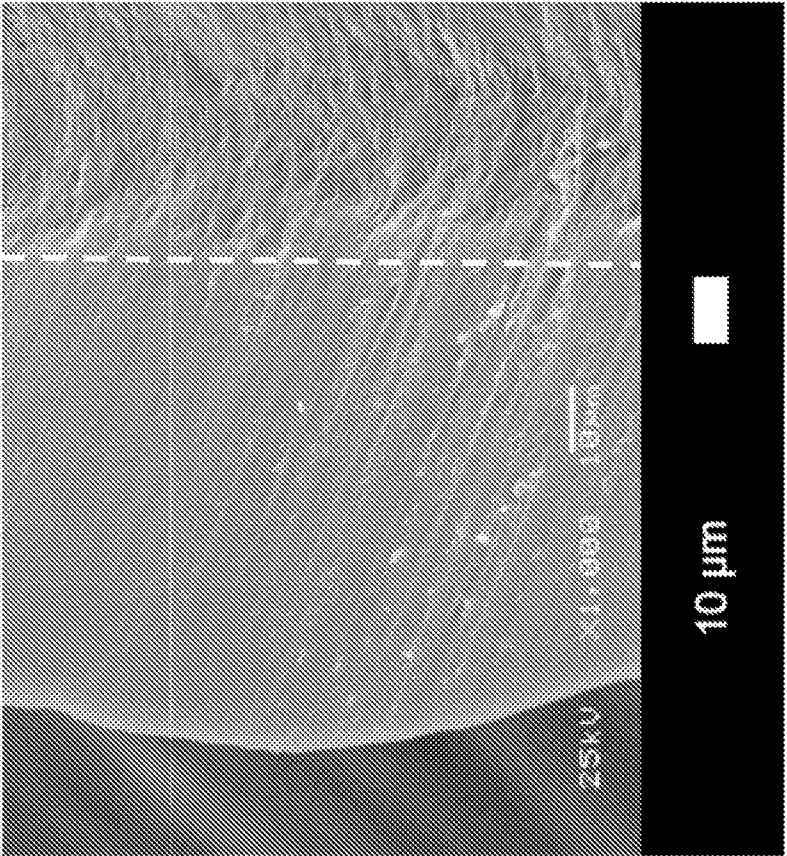


FIG. 6B

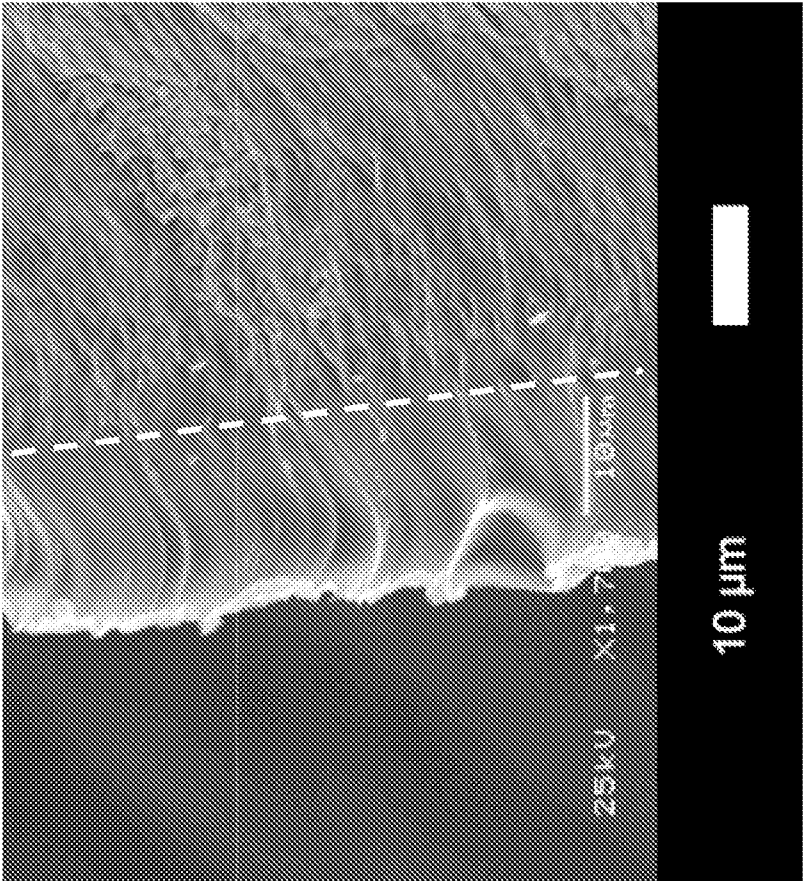


FIG. 6D

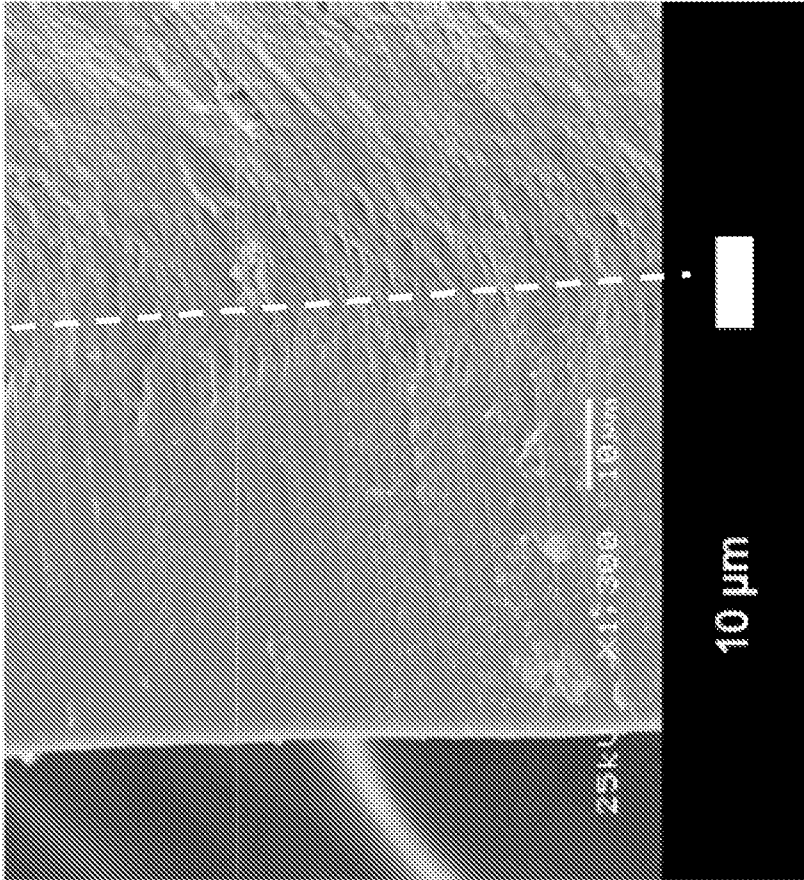


FIG. 6C

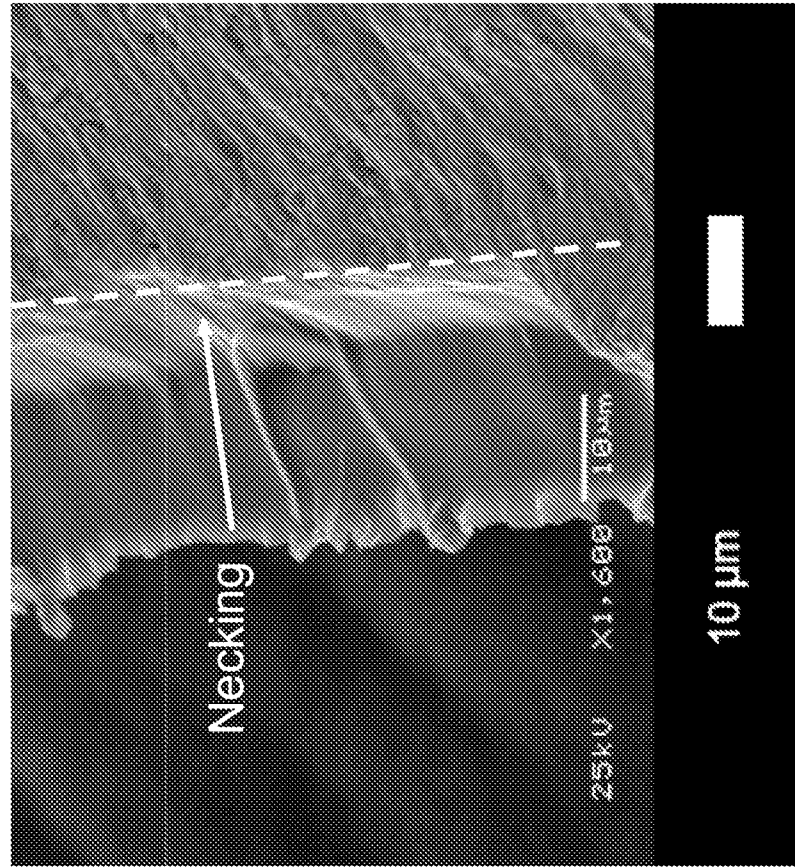


FIG. 6F

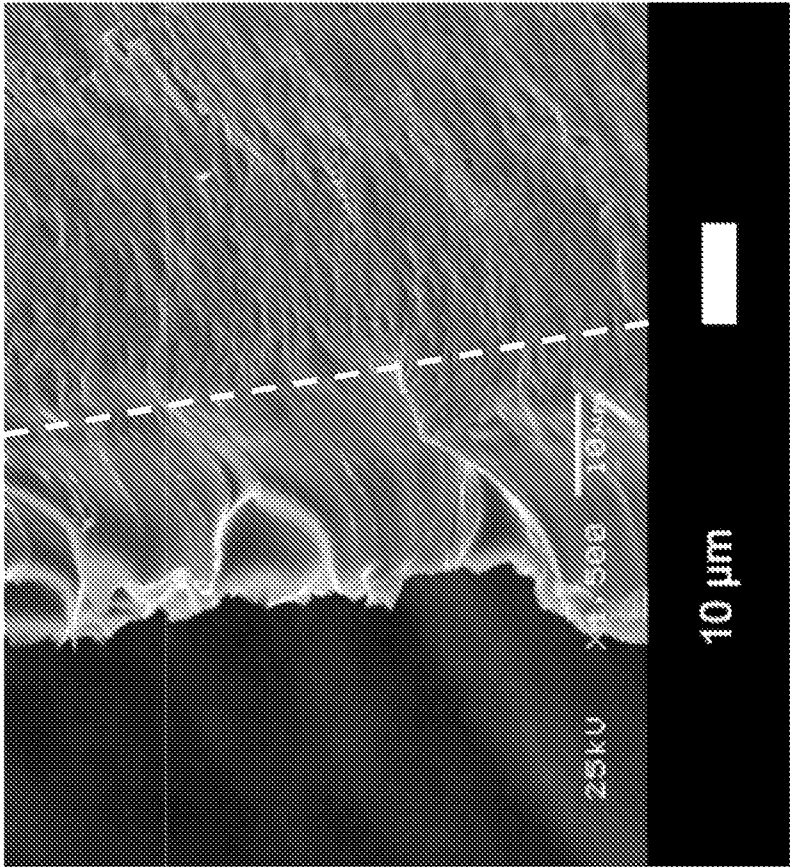


FIG. 6E

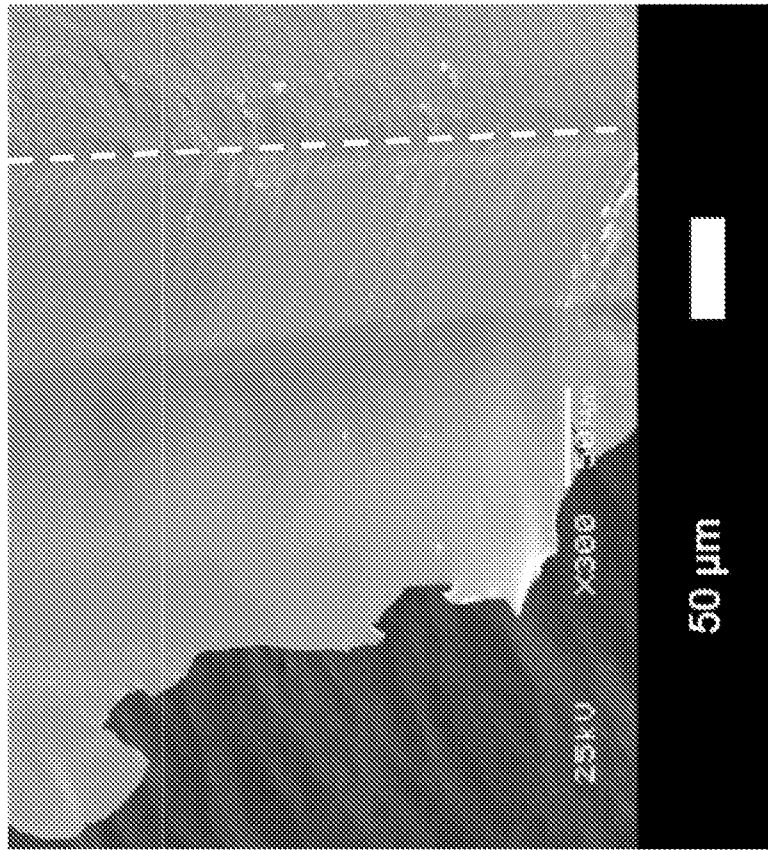


FIG. 6H

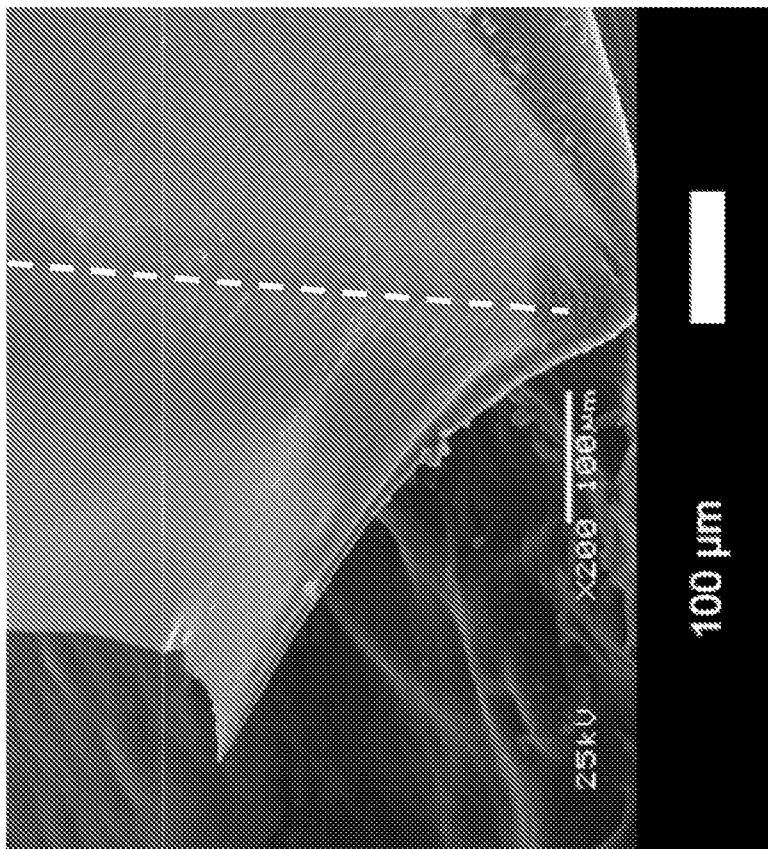


FIG. 6G

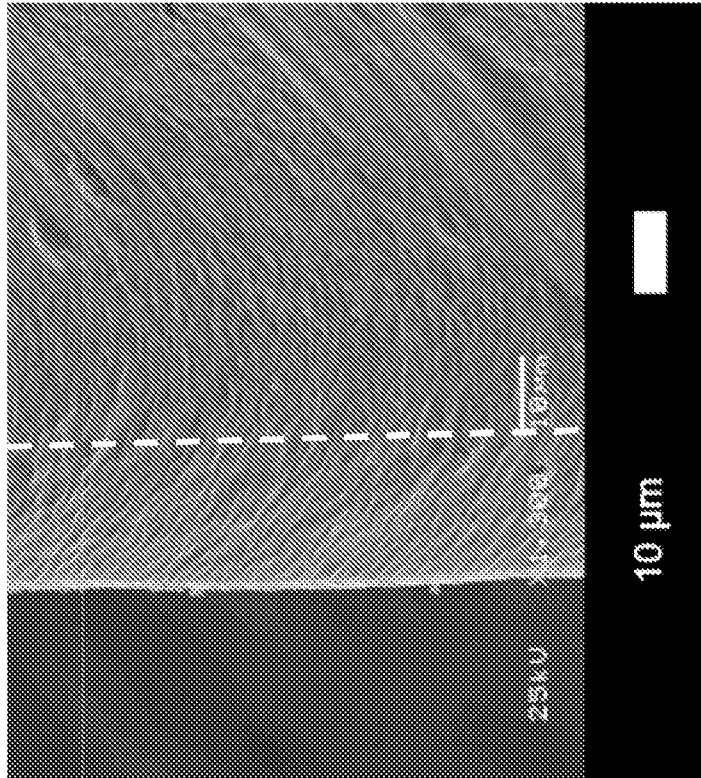


FIG. 6J

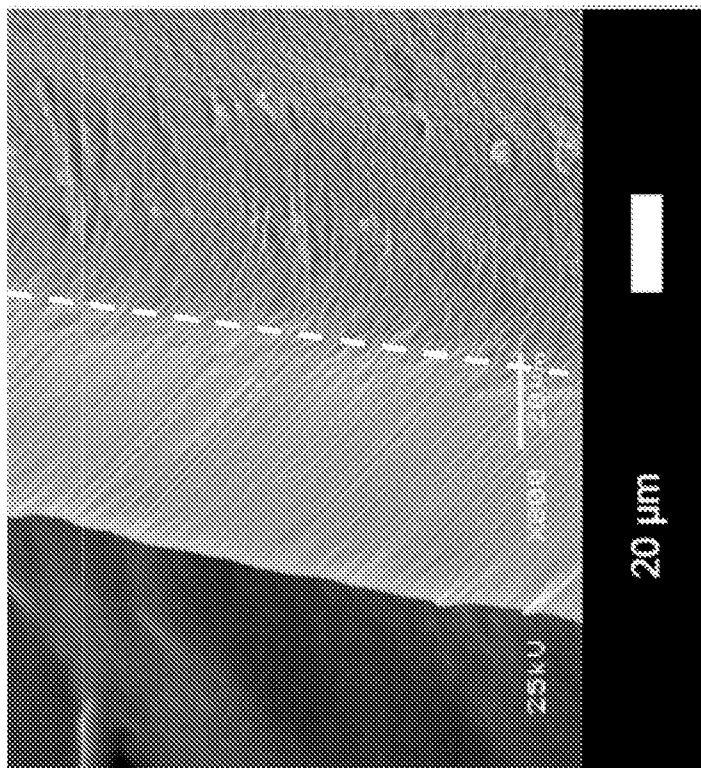


FIG. 6I

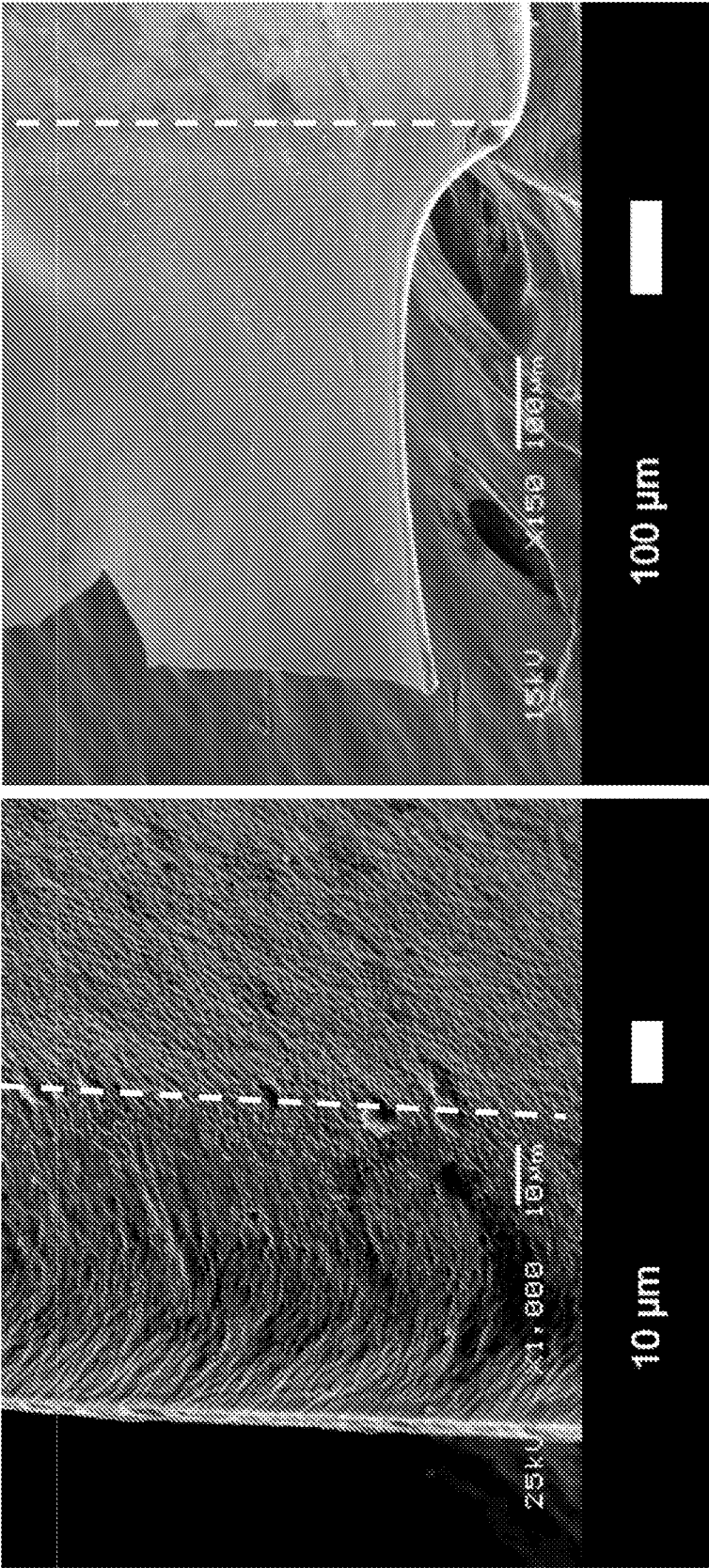


FIG. 6L

FIG. 6K

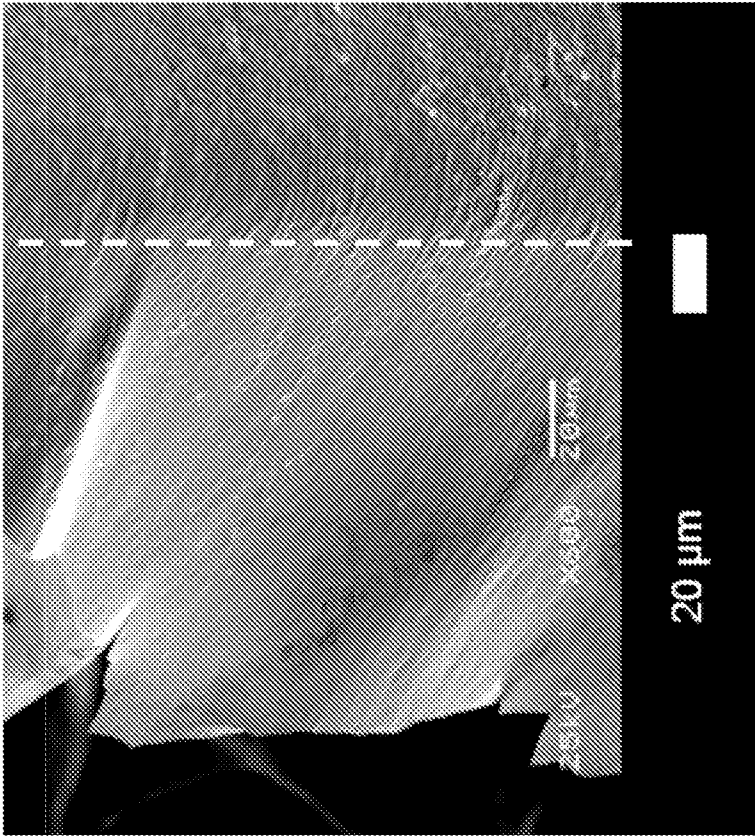


FIG. 6N

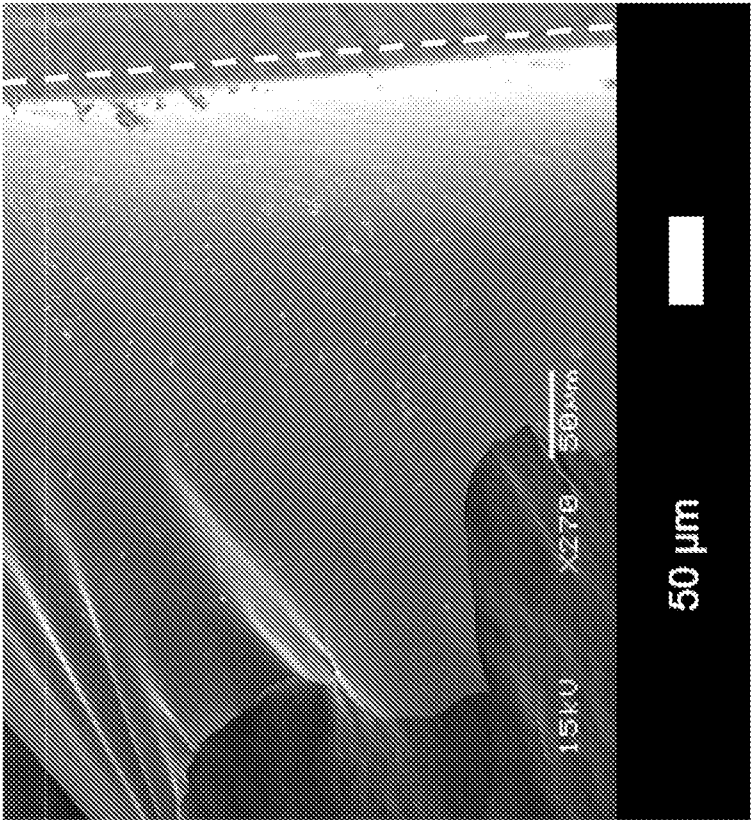


FIG. 6M

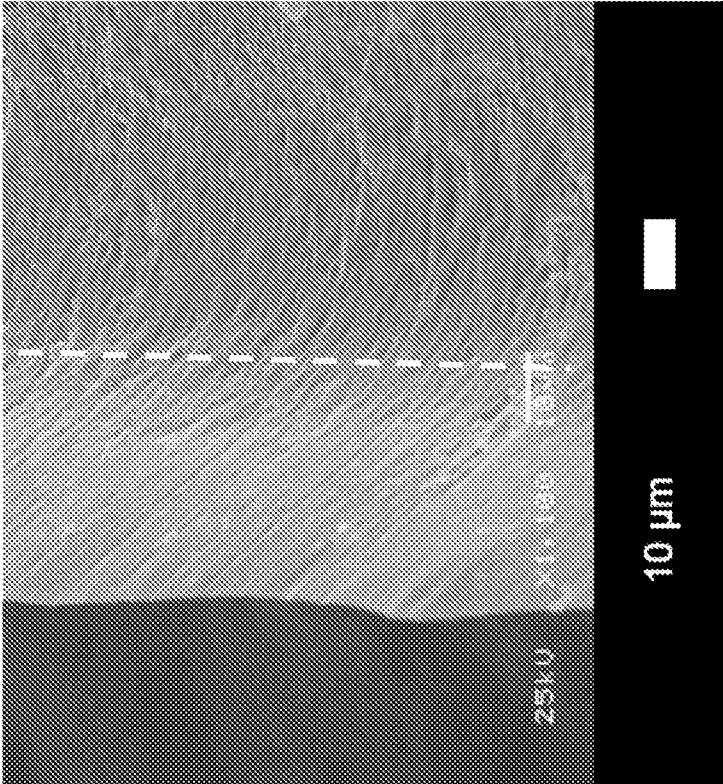


FIG. 6P

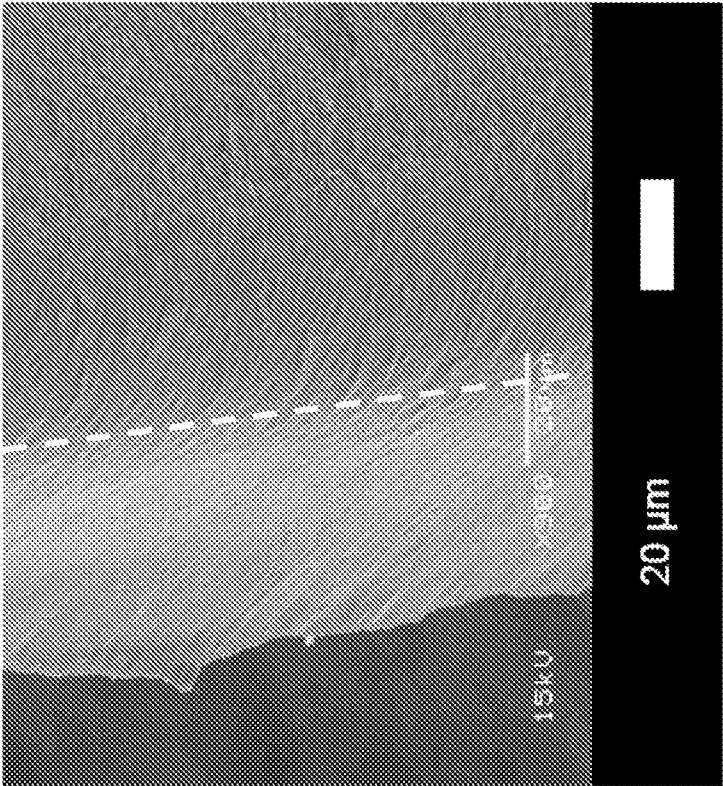
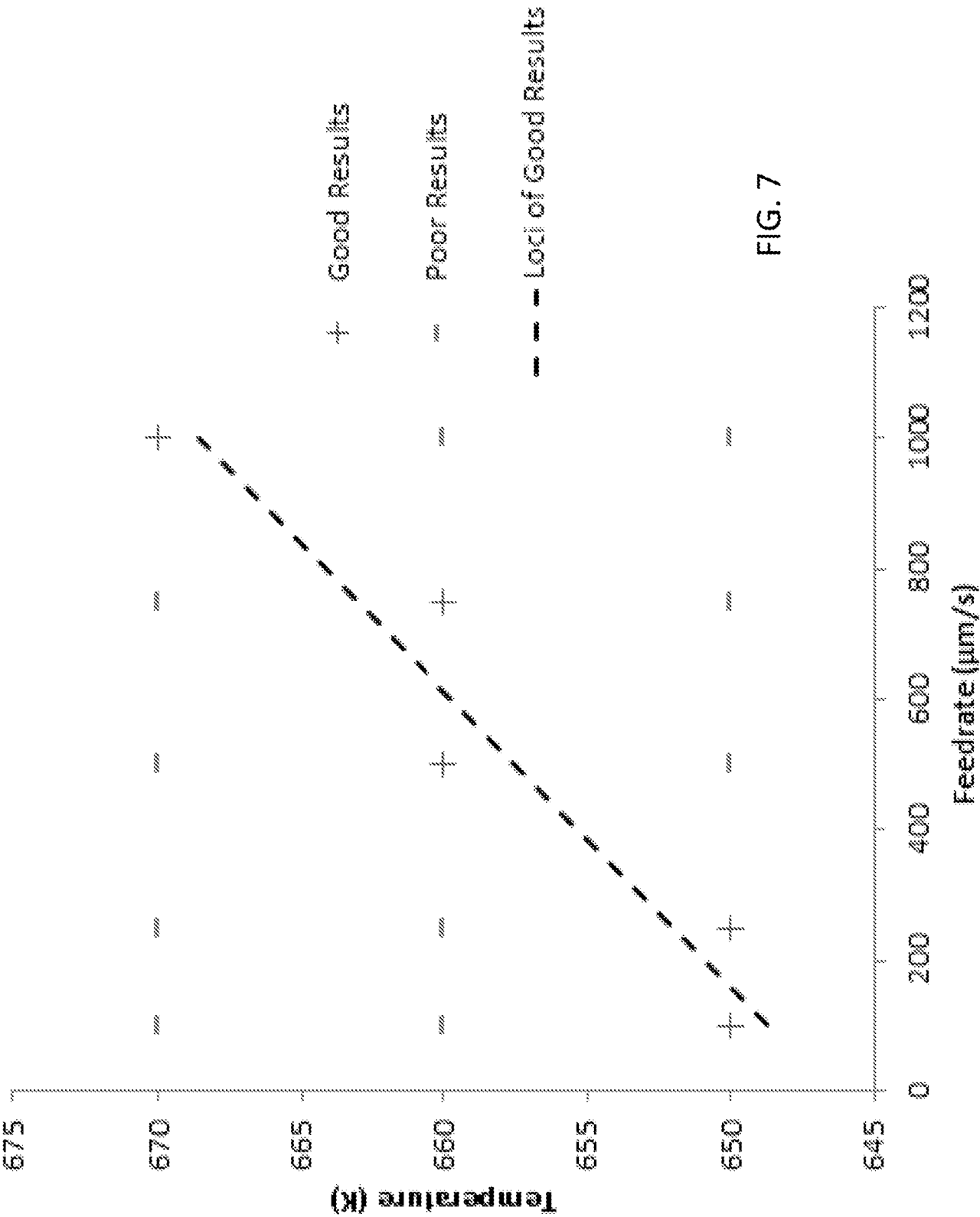


FIG. 6O



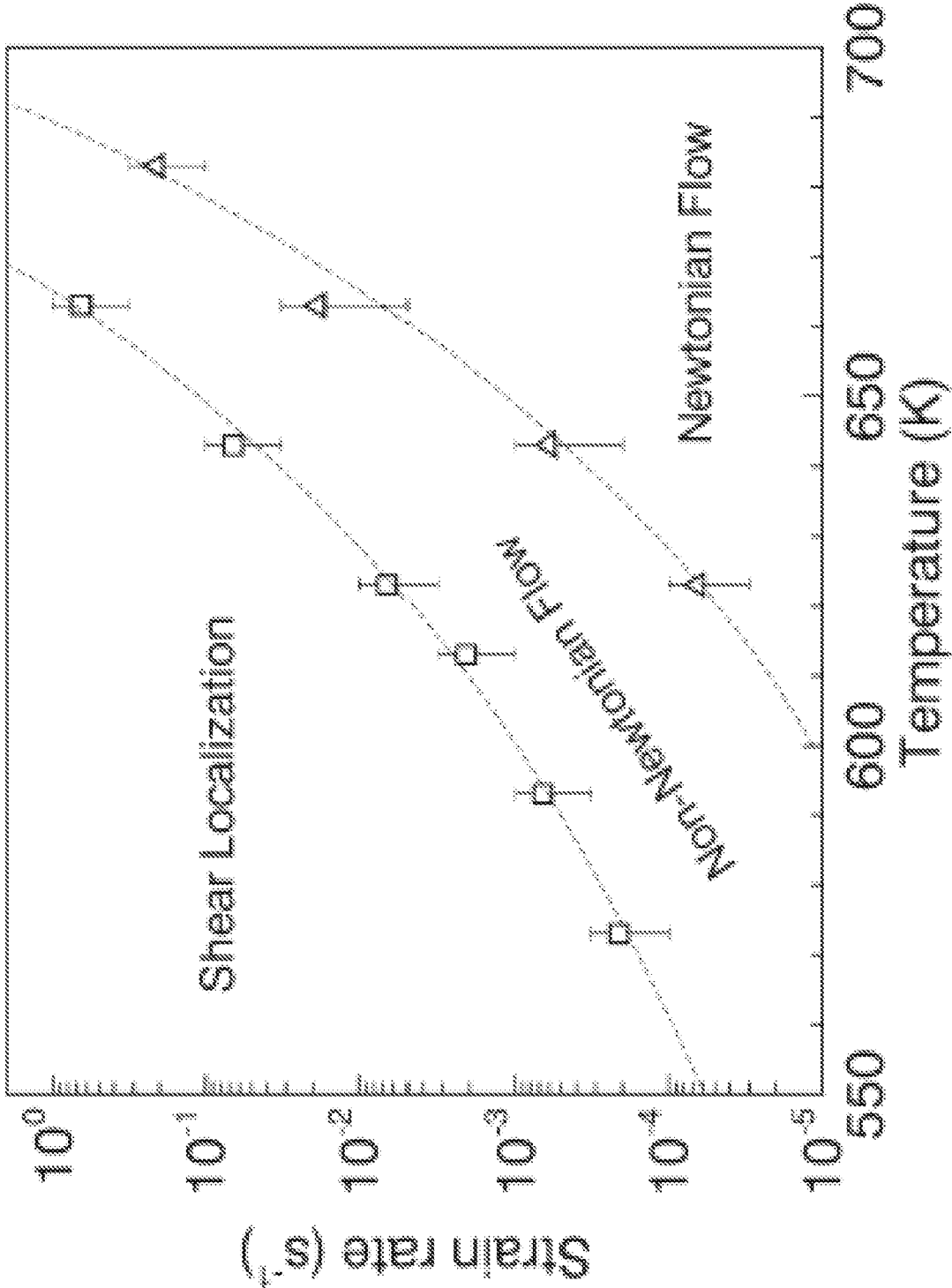


FIG. 8A

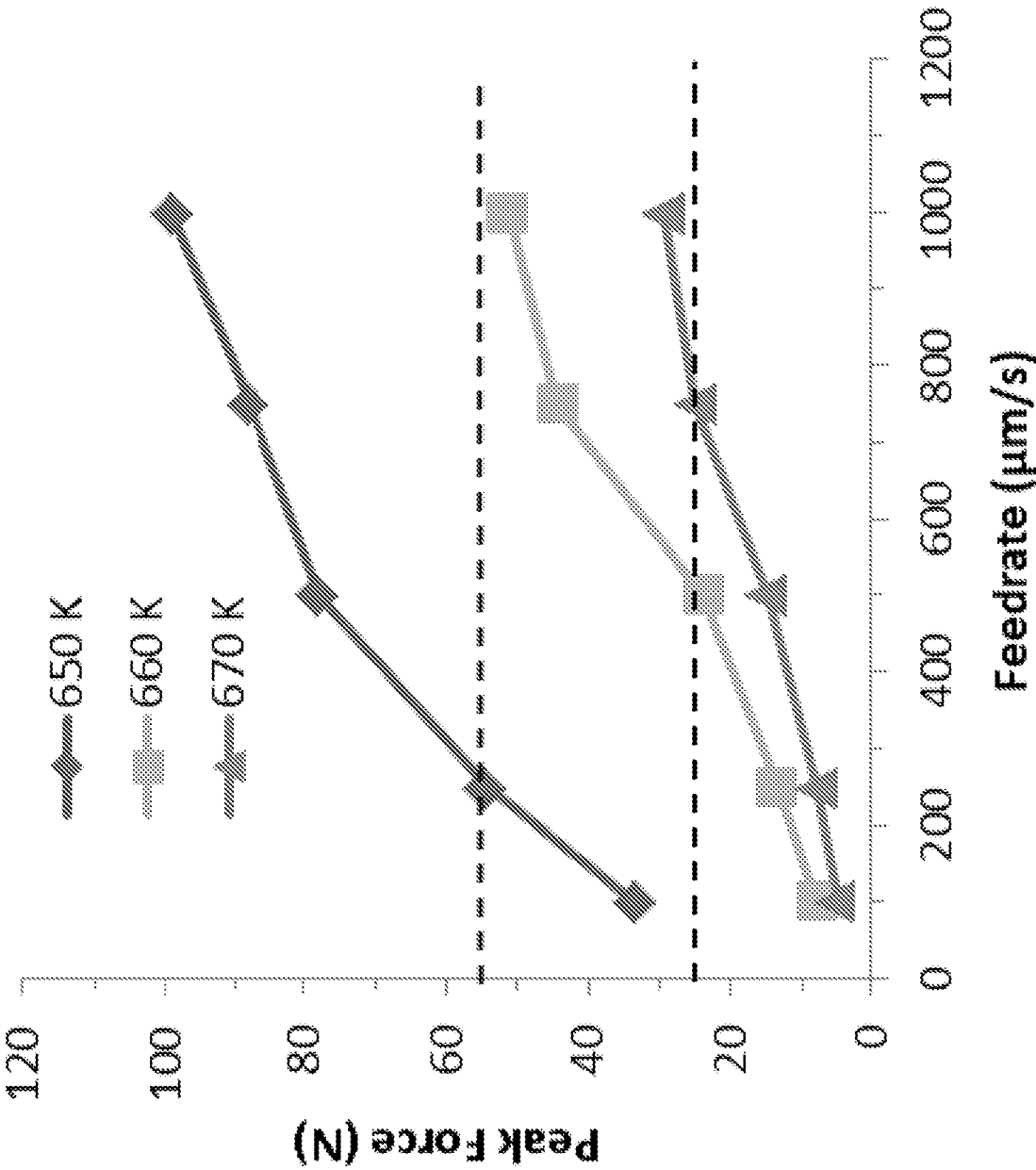


FIG. 8B

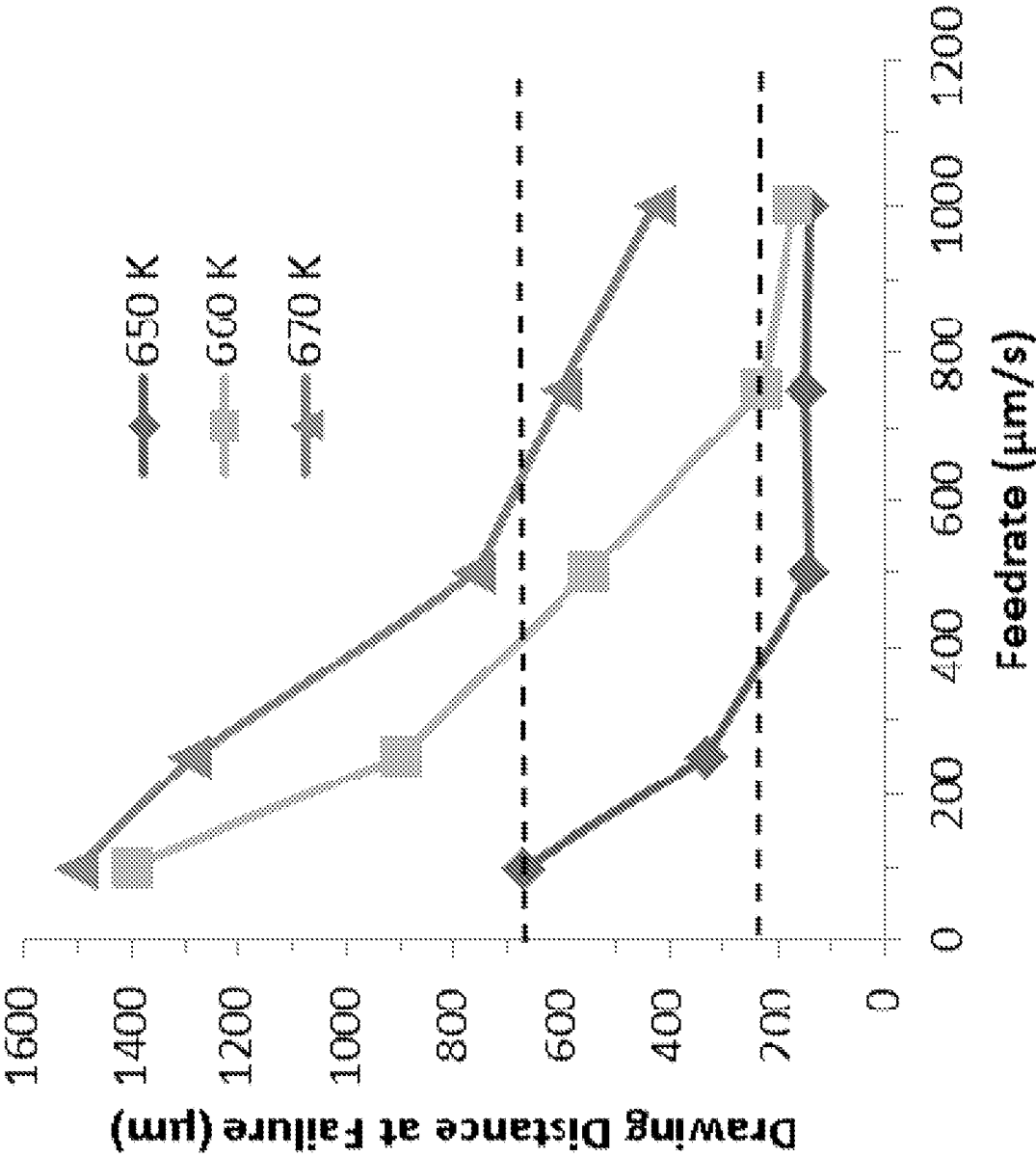


FIG. 8C

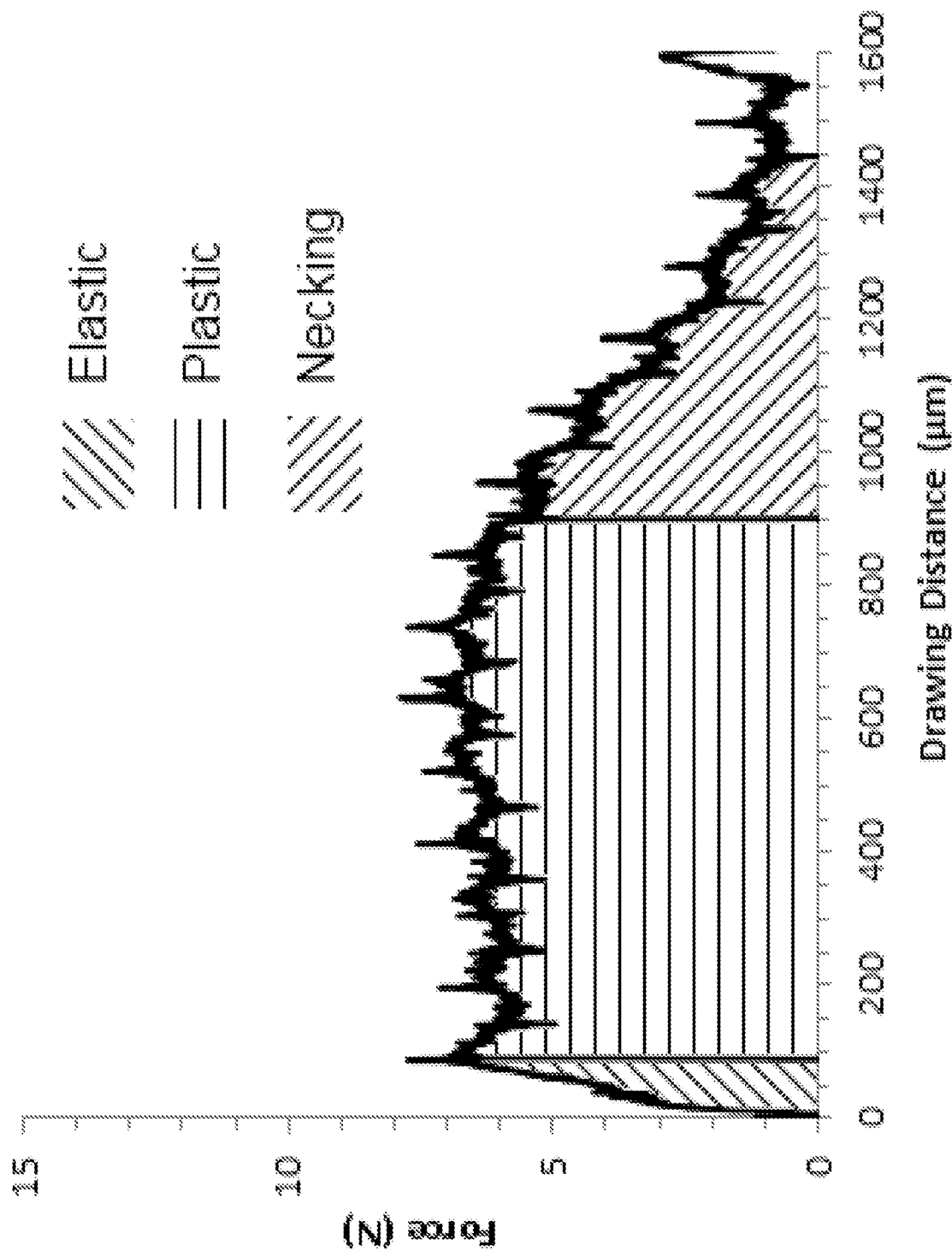


FIG. 9

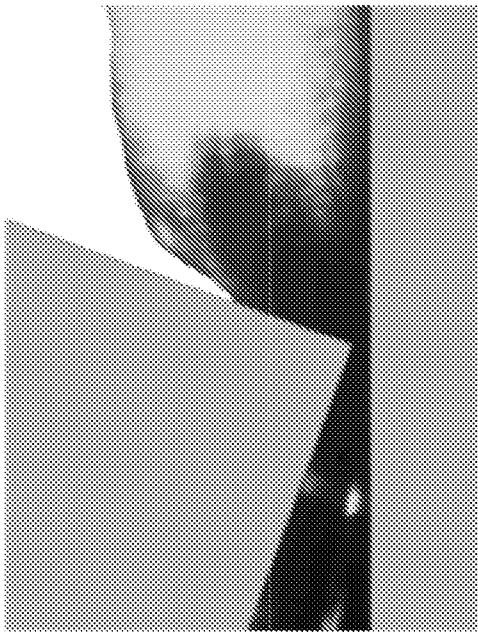


FIG. 10A

0 μm



FIG. 10B

100 μm



FIG. 10C

500 μm



FIG. 10D

900 μm

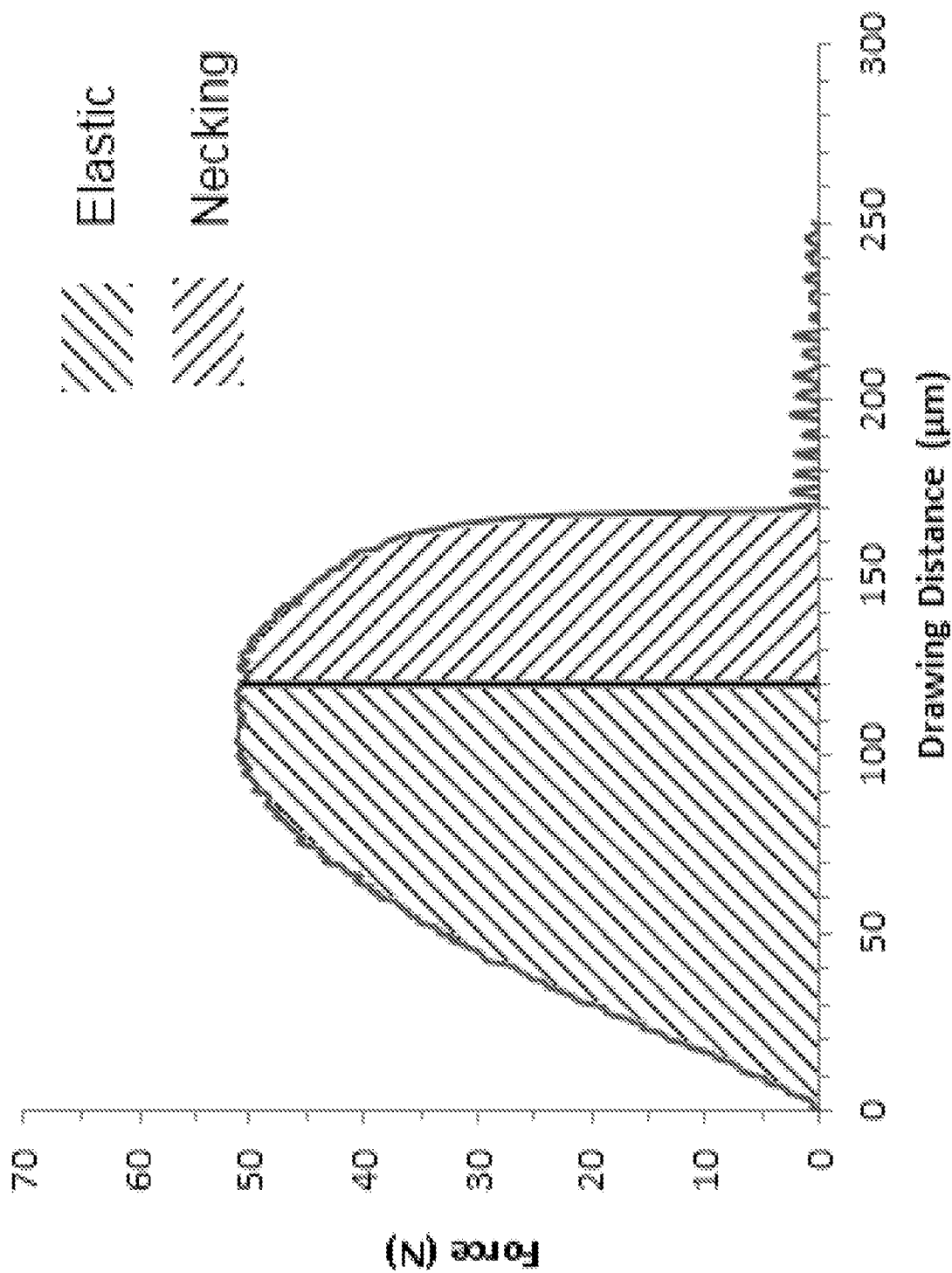


FIG. 11



FIG. 12B

100 μm

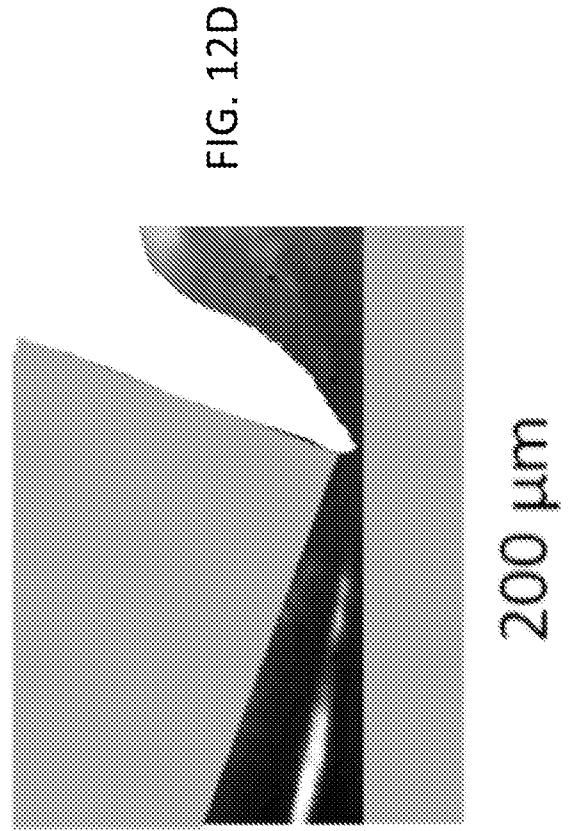


FIG. 12D

200 μm

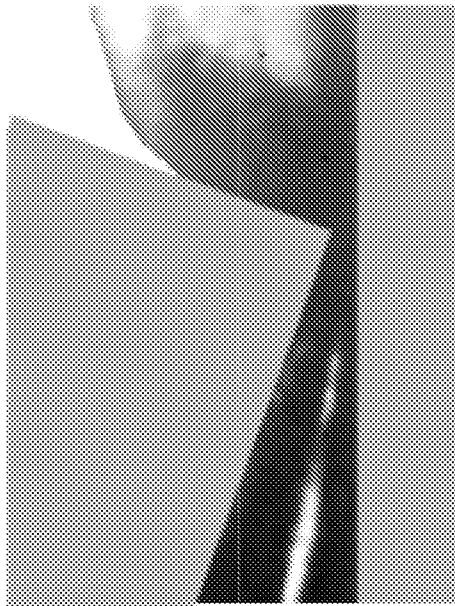


FIG. 12A

0 μm

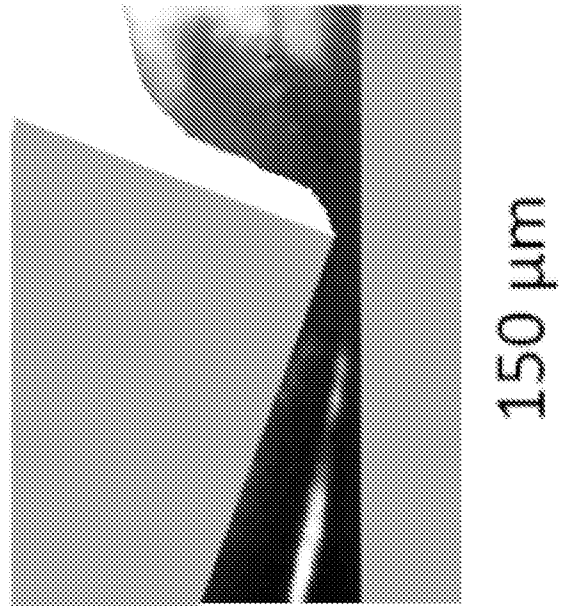


FIG. 12C

150 μm

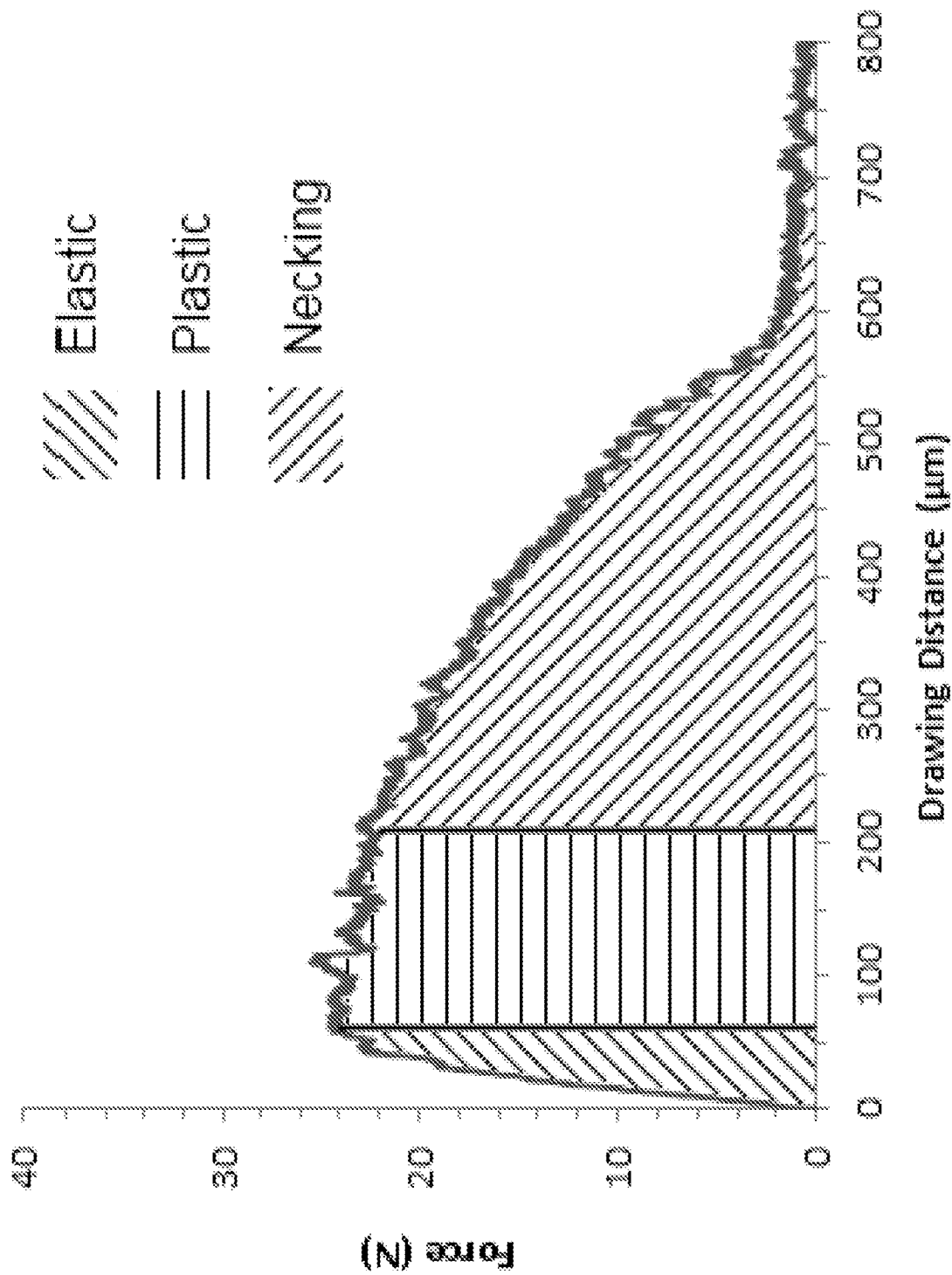


FIG. 13

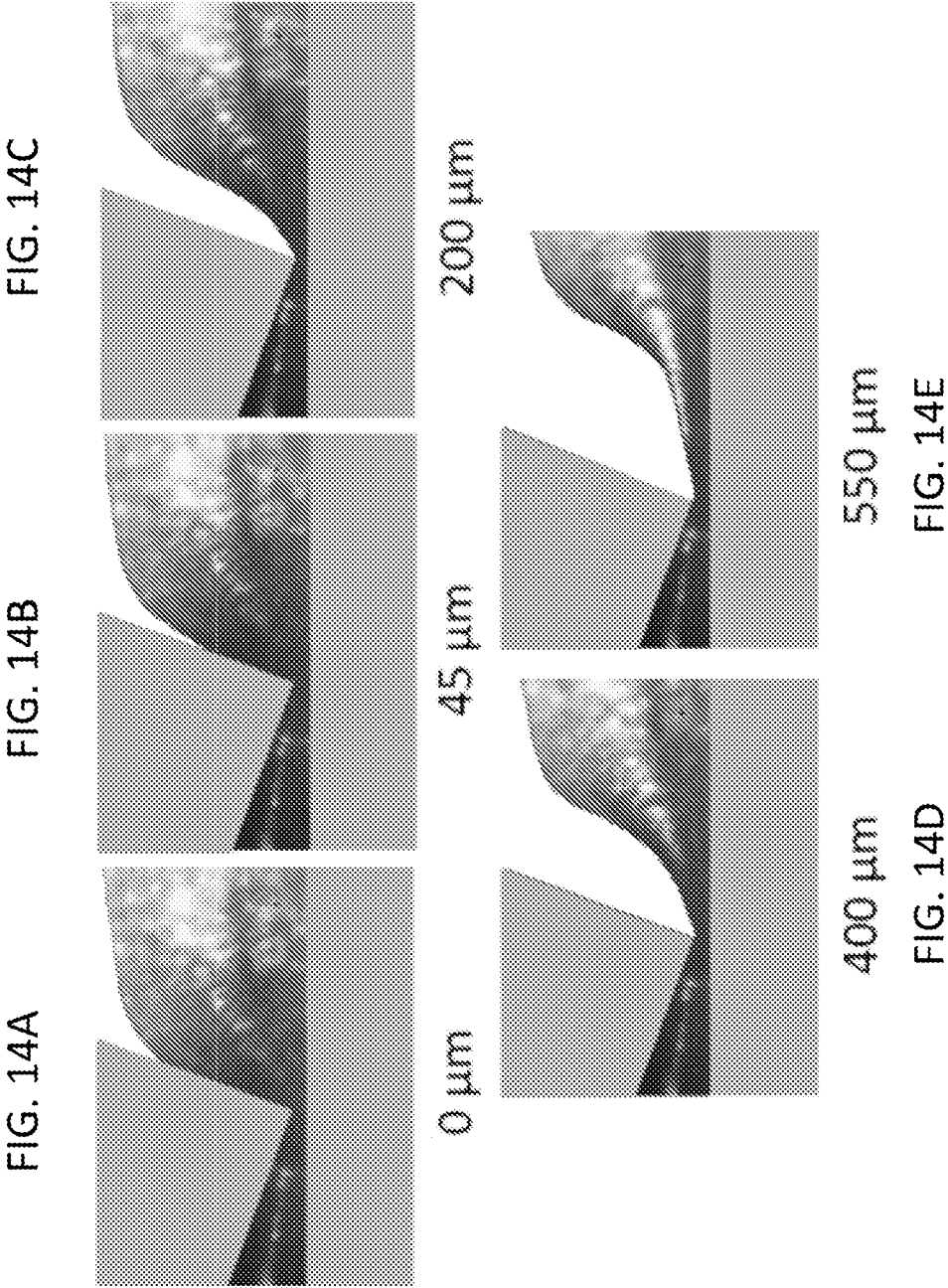


FIG. 15B

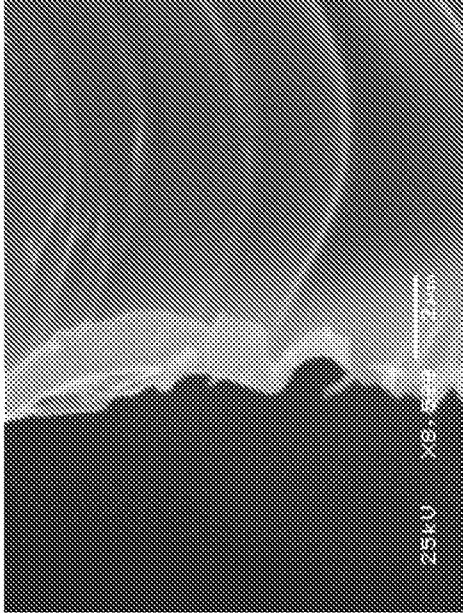


FIG. 15A

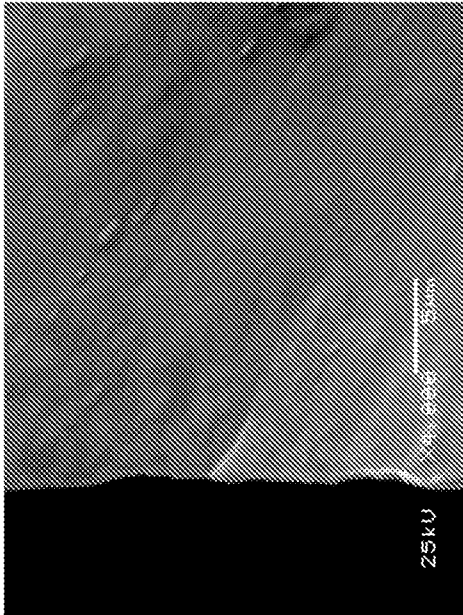


FIG. 15D

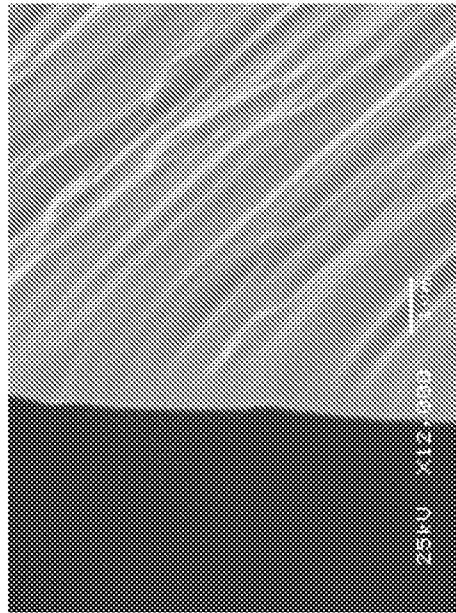


FIG. 15C

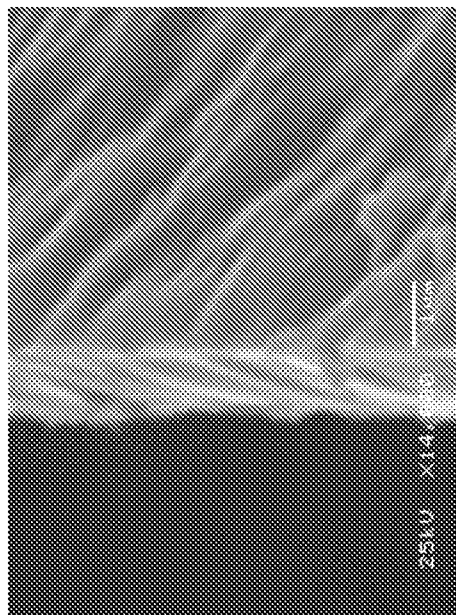




FIG. 16A

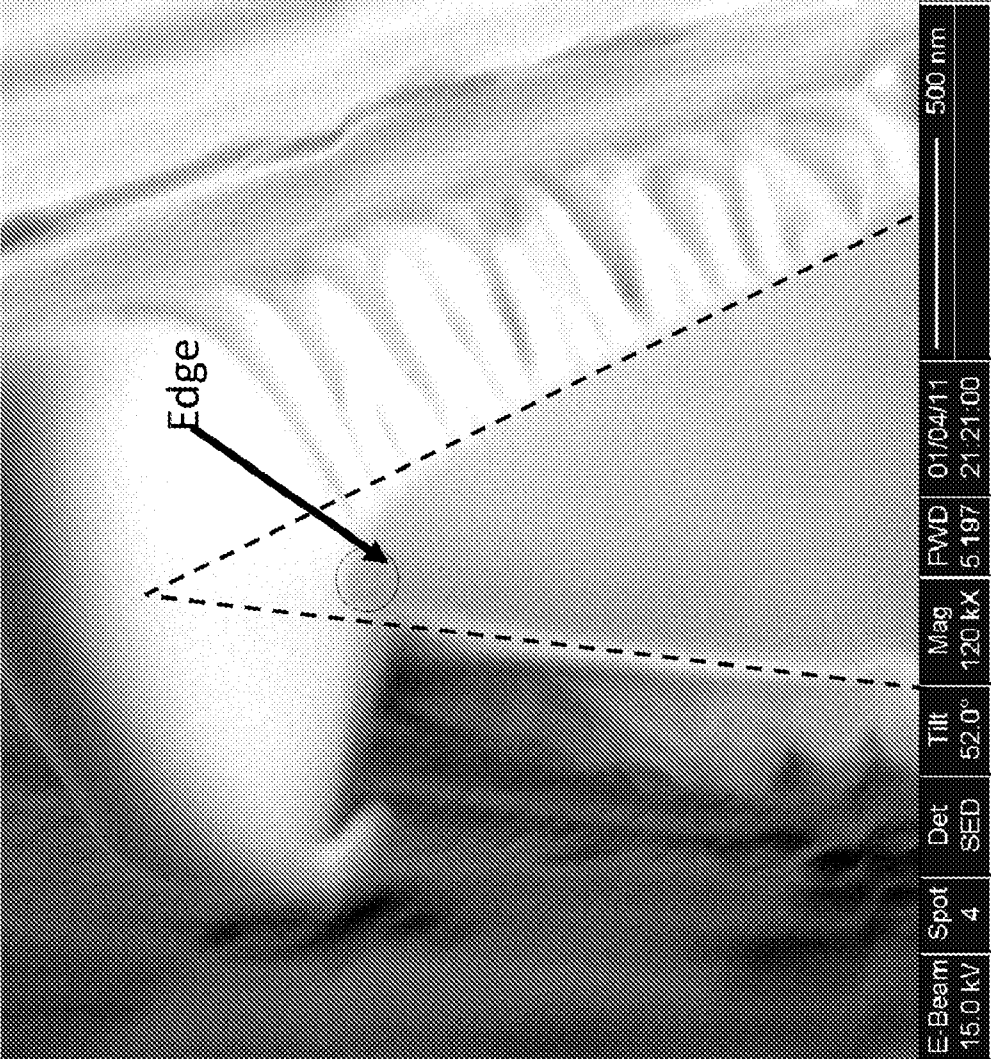


FIG. 16B

A. CLASSIFICATION OF SUBJECT MATTER*A61B 17/32(2006.01)i, C03B 15/00(2006.01)i, C03B 17/00(2006.01)i, A61L 31/02(2006.01)i*

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

A61B 17/32; B25G 1/00; B32B 3/30; B26B 9/00; B22D 23/00; B29D 11/00; C03C 17/00; C03B 11/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: bulk metallic glass, supercool, surgical blade, grade edge

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2008-0155839 A1 (ANDERSON, MARK C.) 03 July 2008 See abstract; paragraphs 32, 33, 50-52; claims 1, 2.	1-12
A	US 2010-0098967 A1 (SCHROERS, JAN et al.) 22 April 2010 See abstract; fig. 1; claims 1, 2, 4.	1-12
A	US 2005-0226955 A1 (YUASA, SEIJI et al.) 13 October 2005 See abstract; fig. 4; claim 1.	1-12
A	US 2008-0034796 A1 (MURAMATSU, NAOKUNI et al.) 14 February 2008 See abstract; fig. 1A; claim 1.	1-12



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

30 JULY 2012 (30.07.2012)

Date of mailing of the international search report

31 JULY 2012 (31.07.2012)

Name and mailing address of the ISA/KR

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City, 302-701, Republic of Korea

Facsimile No. 82-42-472-7140

Authorized officer

KANG, HEE GOK

Telephone No. 82-42-481-8264



INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2012/025903

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