Special purpose Nano-grinding Machine for Fabrication of Different Profiles on Optical Fibers Endfaces

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Optical fiber tips require to be modified in different ways to make them suitable for different applications. It has been well established in the literature that fabricating micro-lenses on optical fiber endfaces can be used to improve light coupling efficiency in optical fiber system, in optical sensors, in scanning electronic microscopy, etc. This paper looks into the feasibility of using nano-grinding technique to produce fiber tips with different profiles. The paper includes description of nano-grinding machine (NGM), determination of grinding parameters, and presents SEM and other optical microscope photographs of some samples of different profiles ground on single mode optical fibers endfaces.

***Index Terms*—** nano grinding, microlenses; lenses, optical fibers, light coupling, ductile mode grinding, nanotechnology, optical sensors, scanning probe microscopy.

I. Introduction

THE NEED to improve light coupling efficiency to eliminate losses in optical fiber applications led to the fabrication of different forms of lenses. These lenses were placed between the light source and the fiber-launching end. The aim was to focus as much light as possible into the center of the fiber. Improvement of light coupling is essential requirement for almost, if not all, optical fiber applications such as telecommunication, optical sensory, optical scanning probe microscopy [1], [2] optical alignment, and illumination.

Early work has seen developments of different designs of external lenses placed between the laser diode (LD) and single mode fiber (SMF) in order to focus the scattered light into the center of SMF. Examples include aspheric lens [3], [4], ball lens [5] plano-convex Lenses [6] two stages of external lenses [7], and others [8]. Hao et al. [9] have used external aspheric plastic lenses to couple the light from a laser diode (LD) to a single mode optical fiber (SMF) in their laser-fiber alignment system. The introduction of optical fiber in such system was to effectively separate laser diode from the final source point used in the alignment system. This prevents the heat generated by the laser diode from deforming the final source point and consequently enhances the stability of the alignment datum reference.

In recent years there has been extensive research and development activity aimed at the design and the realization of optical fiber sensors for a wide range of applications such as chemical, biochemical, biomedical, and environmental sensors. The sensitivity of these sensors can be enhanced by modifying the fiber tip to allow easy access to the evanescent field in fibers thus enabling strong interaction with the analyte. Among the most reported modifications of fiber tips in the literature are the tapered, and the conical tips. Other geometries of optical fibers tips reported to have also been used in optical sensors technology such as D-shaped tips, and tips with slant endfaces.

Different techniques have been reported in the literature pertaining to the methods used for modifying optical fiber endfaces. Chemical etching is one of the techniques that has been attempted by many researchers [10]-[12]. Another technique reported by Mathyssek and Keil [13] involves heating the fiber by electric arc or flame then pulling the fiber to produce a narrow waist, which in turn was either cleaved or heated further until the waist separates. This results in conically tapered lenses. Laser micro machining [14], [15] and focused iron beam milling method [16] have also been reported as a means of direct fabrication of microlenses on SMF on endfaces.

Despite the success of the above-mentioned techniques, most of them have suffered from a common problem i.e. repeatability. In many applications producing identical lens is essential. This was not attainable by any of these techniques. Another common problem of these techniques is the inability to achieve precise desired lens profiles. In chemical etching technique for instance, the use of highly active chemical solution to etch the glass away, such as hydrofluoric acid, renders the technique suitable only for highly controlled laboratory environments. The technique is also limited on the range of lens geometries that can be produced. Heating and pulling technique results in tapering the fiber core diameter and consequently reducing the light collection angle. Yet another drawback of this technique is that of lens centering. Hillerich et.al [17] showed that coupling loss increases drastically when lens/core center offset is more than 5 μm. In order to operate efficiently, lenses must be centered to within a fraction of fiber core diameter. Such a resolution is not attainable with this technique.

The work presented here is a novel approach to producing microlenses on optical fiber endfaces by mechanical nano-grinding technique. This technique promises more control on lens centering and lens profile as well as ensuring profile repeatability. Nano-grinding is also capable, with relative ease, of producing conical tips, tapered tips, wedged tips, etc.

This work started by first determining the grinding parameters that can be used to achieve ductile mode grinding of a single mode optical fiber. Grinding optical fibers presented a huge challenge owing to the brittleness of their materials and the fragility of the fiber structure (ϕ=125 μm). To perform this task a special purpose Nano-Grinding Machine (NGM) was built. The machine was capable of producing infeed rates in nanometer range. Such infeed rates ensure that the material critical depth of cut was not exceeded. The critical depth of cut of the optical fiber material was determined using nano-scratch tests. Further experiments were conducted using NGM to determine suitable grinding parameters such as the infeed rate, turning speed, and grit size. Once these parameters were established, different lens profiles were fabricated. The following sections will include summary of the nano-scratch test results, description of NGM, grinding parameters experiments, and finally fabrication of the fiber-tip lenses with different profiles.

II. The Nano-Scratch Test

The best practical way to mimic grinding is to conduct scratch test. For this purpose nano-scratch tests were conducted on a sheet of optical fiber material using nano-scratch testing machine. Fig. 1 below show three scratches made by 500 mN load and 300 mN load using 5 μm ball indenter. The load was increase from zero on left side of the sheet and gradually increased until reached the set value on the right. Atomic Force Microscope (AFM) measurement conducted at the location marked with the arrow and the circle on the figure, showed a depth of cut equal to 440 nm as shown in Fig. 2. This particular location indicates the transitional region between ductile and brittle material removal.

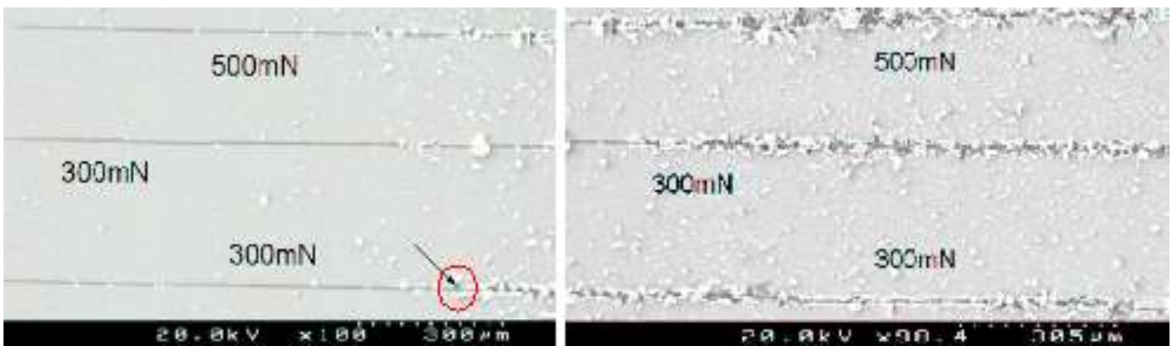

Fig. 1. Nano scratches on optical fiber material

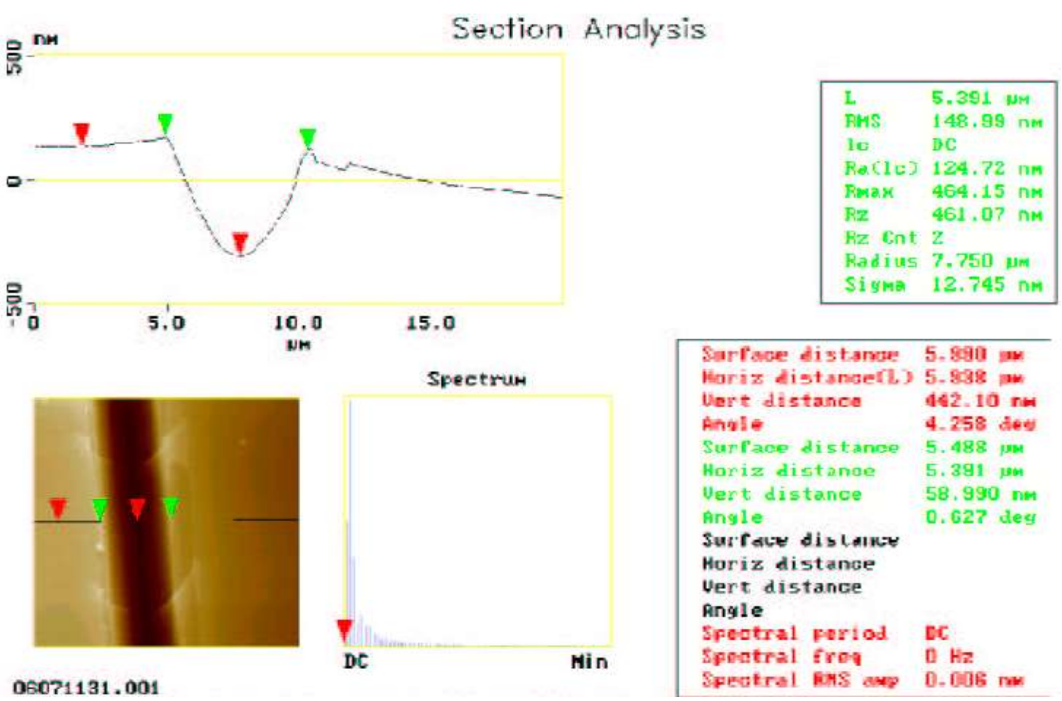

Fig. 2. AFM section analysis showing critical depth of cut if 442 nm.

It follows from this is that in order to be able to grind optical fiber materials, the grinding machine to be devised must be capable of producing infeed rates of less than 440 nm/rev, which is the critical depth of cut, based on the nano-scratch test. The following section will include description of the nano-grinding machine that was specifically built and used in this work.

III. The Nano-Grinding Machine (NGM)

Ductile-mode grinding of brittle materials such as optical fiber material demands grinding apparatus that is capable of achieving depths of cut in submicron range. Such criterion can only be attained by utilizing state-of-the-art actuation mechanisms guided by closed loop feedback control and spindle system with run out errors of only few nano-meters. Vibrations will also need to be mitigated to amplitudes below the critical depth, or if possible, eliminated all together. In addition, this machine unlike those machines developed specifically for grinding of brittle materials [18], has to deal with the inherited structural weakness of a bare SMF. This has imposed an extra constrain on the way the fiber is handled, and on the amount and type of forces that the fiber can withstand before snapping. The miniature size of SMF posed another constrain for which a solution was needed. With such size it is extremely difficult to position and align the fiber with respect to grinding tool and the axis of spinning without some means of magnification. This has necessitated the need for a high magnification visual system. Fig. 3 shows NGM which is comprised from the following components: air-bearing spindle, vibration isolation table, optical fiber positioning system, high magnification imaging system, nano-stage, and control system. The grinding surface comprised of commercially available AngstromLap™ films with grit size ranging between 0.5 to 5 μm stuck on aluminum disk mounted on the air bearing spindle.

Once the machine was built it was used to determine the suitable grinding parameters that can be used to ground lenses on optical fibers endfaces.

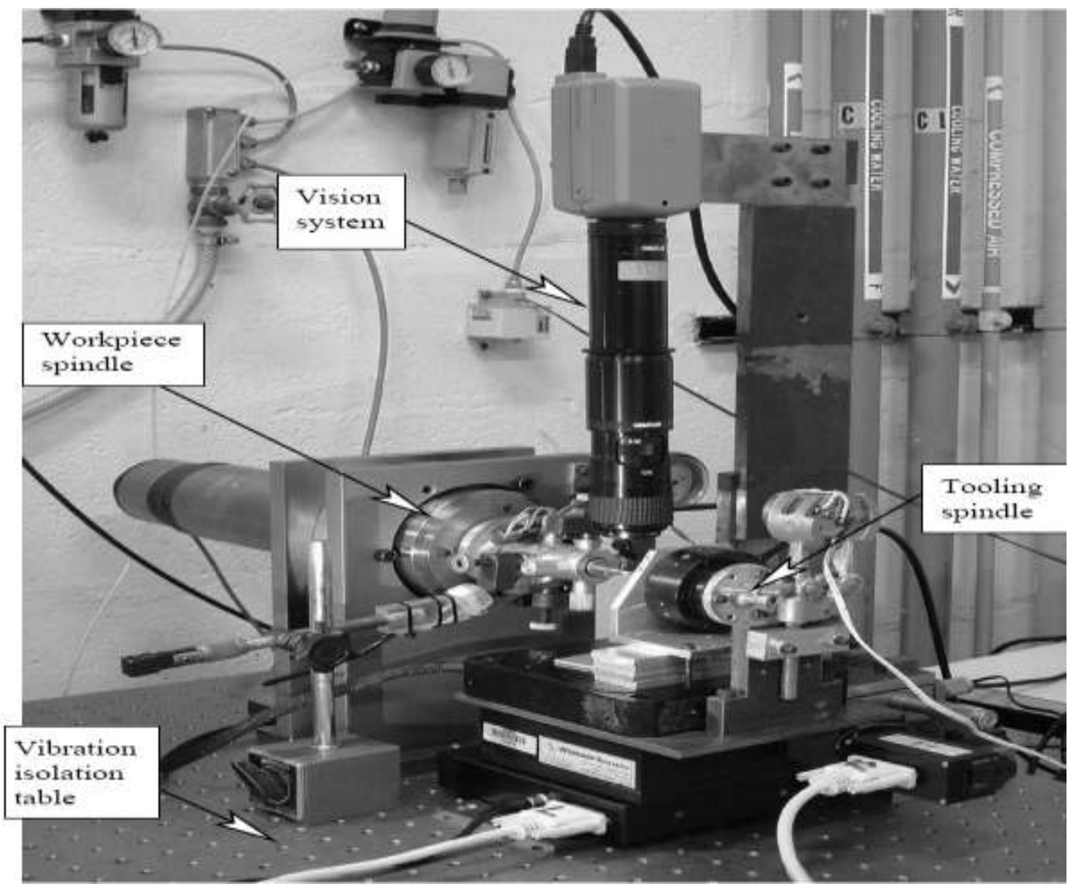

Fig. 3. Photograph of the nano-grinding machine (NGM)

IV. Grinding Parameters

In order to determine the suitable grinding parameter that could be used to grind micro-lenses on SMF endface, few experiments were conducted on NGM. Fig. 4 below shows the surface quality of fiber endfaces ground using spindle speed ranging from 2000 - 8000 rpm and grits size of 1 μm. The result showed hardly any effect of the spindle speed on the surface quality.

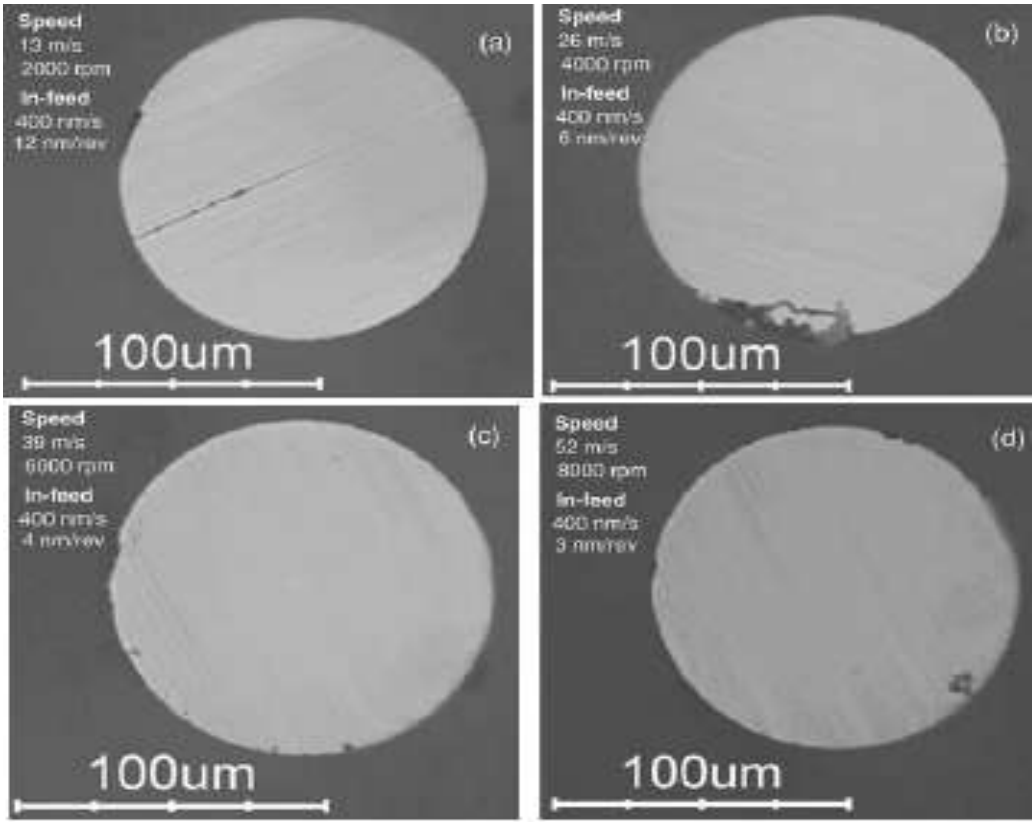

Fig. 4. The effect of spindle speed on surface quality

Further experiments were conducted to examine the effect of infeed rate on surface finish. Samples of optical microscopic pictures for fiber endfaces ground using grit size of 1 μm and spindle speed of 6000 rpm are shown in Figure 5. Table I below summarizes the results for the surface roughness measurements conducted on the ground fibers. The results showed that within the range of the infeed rate used, the difference in surface roughness was insignificant. Based on these results it was decided to adopt spindle speed of 6000 rpm and infeed rate of 1500nm/s (maximum for the nano-stage) which corresponds to infeed rate of 15nm/rev. The latter value is of special interest as it represents the depth of cut at with which the material is removed for every revolution, which is well below the maximum depth of cut for ductile material removal determined using the nano-scratch test (440 nm). It was then concluded form these results that using 1 μm grits size, and infeed rate of 15 nm/rev, the NGM should be capable of grounding optical fibers within the ductile-mode region. This should ensure high surface finish, high form accuracy as well as high surface integrity.

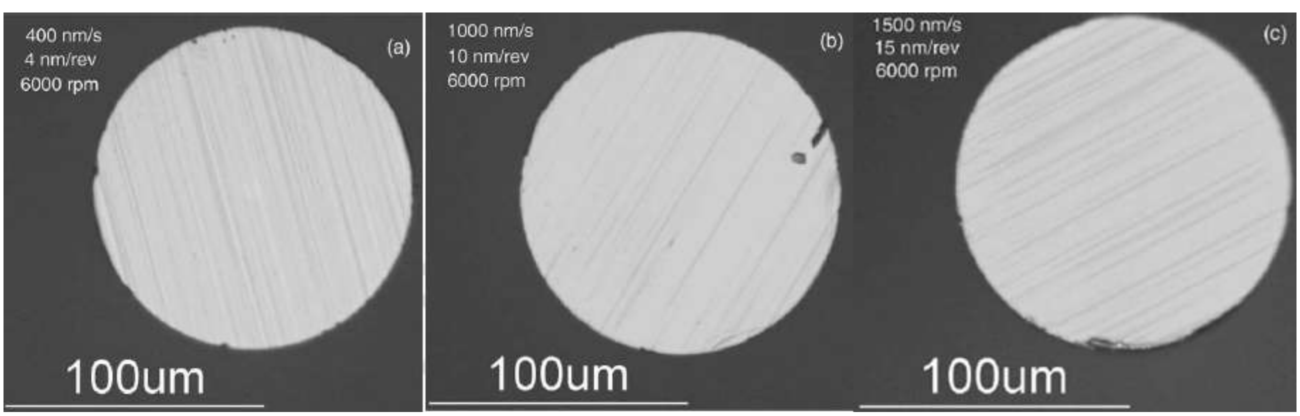

Fig. 5. the effect of infeed rate on surface quality

Table 1: In-feed rates and surface finish R_a

Speed (rpm)	2000	8000	2000	8000	2000	8000
(m/s)	13	52	13	52	13	52
In-feed rate (nm/rev)	12	3	30	7.5	45	11.25
(nm/s)	400	400	1000	1000	1500	1500
R_a (nm)	4.50	3.00	4.55	4.00	4.80	4.00

More experiments were conducted to see if it would be possible to use bigger grits size, since smaller grits are more prone to clogging by debris. The results in Figure 6 show that it was not possible to obtain ductile material removal using 5 μm grits regardless of the infeed rate. When 3 μm grits were used the results showed regions of ductile and brittle material removal indicating that grinding was taking place just at the borderline between the two modes. Ductile material removal was only possible at very small infeed rate of 0.25 nm/rev as can be seen in Figure 7c.

In order to check for subsurface cracks, one ground sample was milled using Forced Ion Beam (FIB) machine and consequently examined under scanning electron microscope (SEM). The images shown in Figure 8 revealed no evidence of any subsurface cracks.

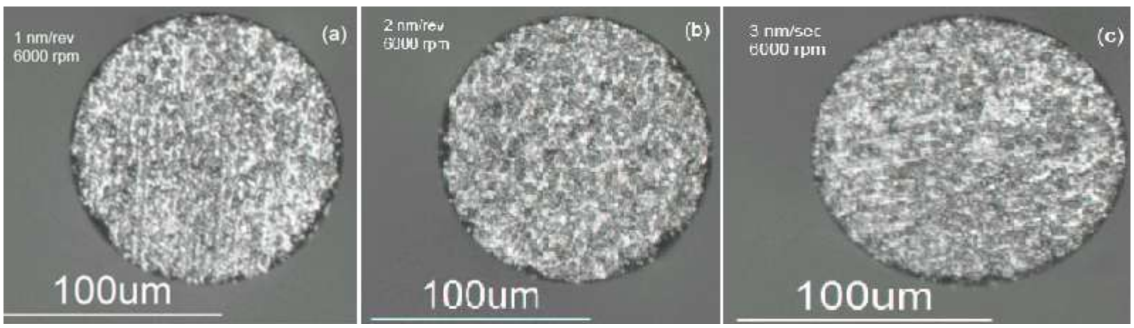

Fig. 6. Optical fiber endfaces ground with 5μm grits

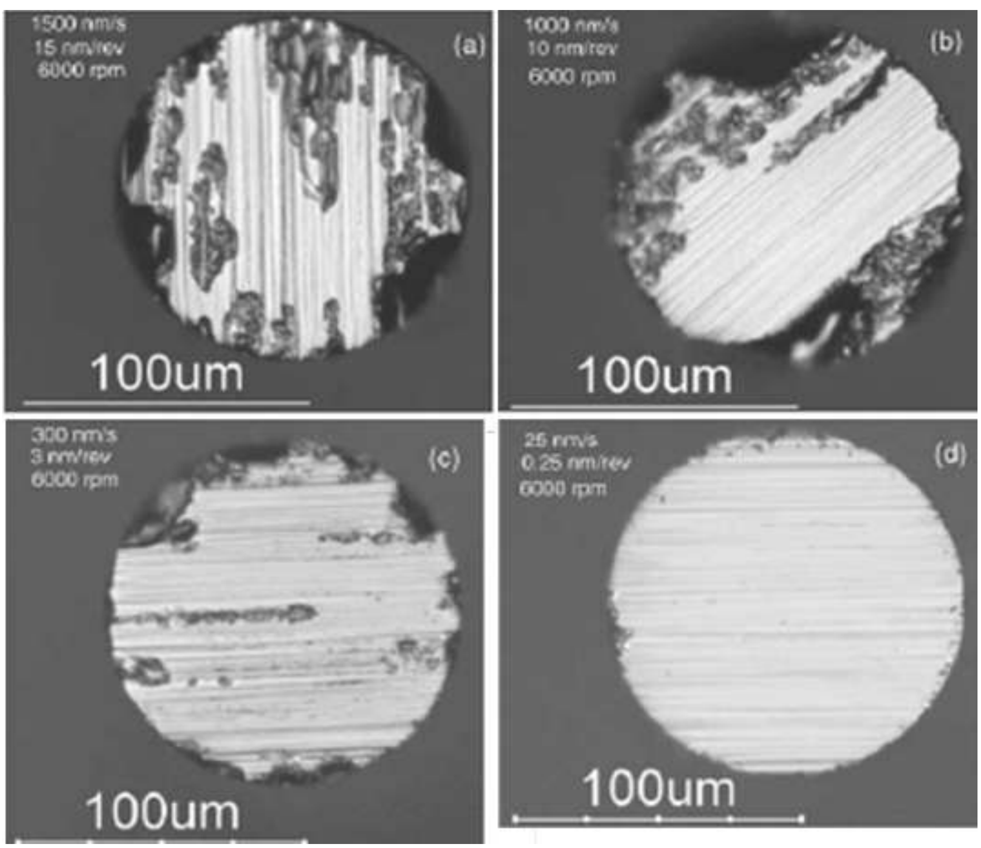

Fig. 7. Optical fiber endfaces ground with 3 μm grits

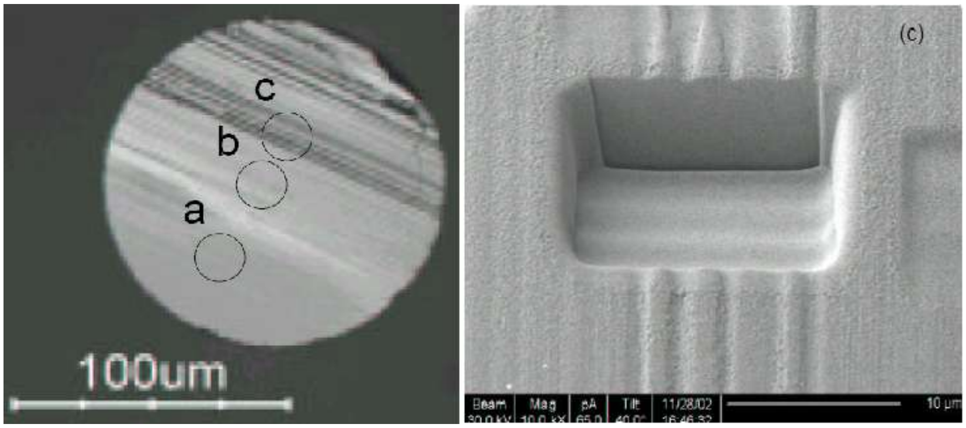

Fig. 8. SEM photograph for a hole drilled using FIB on a ground optical fiber endface (region C)

From the above experiments it was concluded that NGM with AgustronLAB films of 1 µm grits and at infeed rate of 15 nm/rev can be used to ground optical endfaces with high quality surface finish (Ra 4nm) and free from any subsurface cracks.

Once this was established the flowing step was to try to ground endfaces with different profiles on single mode optical fibers.

V. Fabrication of Fiber Endface Micro-lenses

Conical and tapered lenses have seen a wide range of applications. Examples of using these lenses have been reported in areas such as scanning near-field optical microscopy [19], air pollution control [20] and detection of specific antibodies in humans [21]. These lenses are mostly produced either by chemical etching or by heating and pulling technique. This research shows that conical and tapered lenses can be successfully fabricated using mechanical grinding. The advantage of using mechanical grinding over other techniques is that it is more controllable and more flexible, thus ensures the repeatability and the diversity of the lens profiles that can be made. It also eliminates the need for handling highly dangerous chemicals such as HF. Furthermore, the reduction of the core size, a problem associated with heating and pulling method, is no longer an issue with the nano-grinding technique.

Starting from cleaved endfaces, a wide range of conical lenses with a variety of cone angles can be made by appropriately orientating the grinding tool with respect to the fiber endface. Figure 9 shows an example of two conical lenses made with internal conical angles of 68° and 90° degrees. This kind of lenses could be made in just 45 seconds.

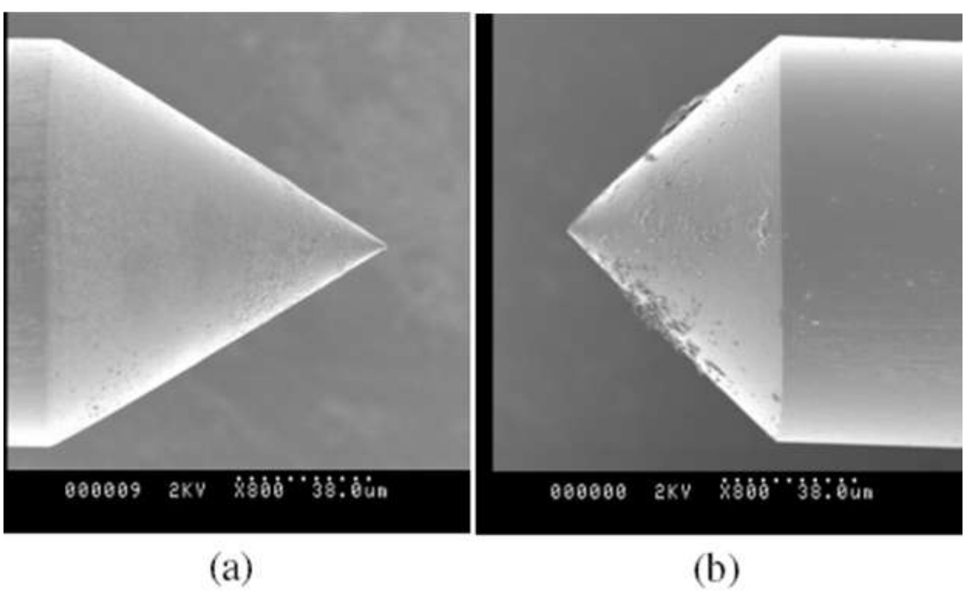

Fig. 9. SEM photographs for ground conical lenses made using NGM: a) cone angle 68°, b) cone angle 90°

It was equally possible to produce lenses with other different profiles such as wedged profiles, slant profile, and D-shaped lenses.

D-shaped profiles are another interesting form of optical fiber endfaces that have recently been associated with optical sensor technology. Examples of using this type of endface include interferometric antenna for microcellular mobile communication system [22], and evanescent wave methane sensor [23]. D-shape endfaces are produced by removing the cladding to a certain length from the tip thereby exposing the core. This gives access to evanescent wave region where sensing takes place. The D-shape cross-section is traditionally obtained by pulling the fiber from a D-shaped preform. In this work nano-grinding has been successfully used to fabricate this type of endfaces. Figure 10 shows, among other profiles, a side view of a D-shape endface produced using nano-grinding. Grinding of D-shape endfaces took place at the edge of the grinding film. The fiber was oriented with an angle of 90° with respect to the grinding film. Grinding was carried out under similar conditions to those used with oblique profiles.

The use of wedge-shaped fiber tips as an effective means for improving light coupling efficiency of optical fibers have been explored by many researches [24] –[26]. Shah et al. [27] reported that well-designed wedge shaped fiber endface can achieve maximum light coupling efficiency of 47 %, much higher than that of flat endface at only 20%. One particular aspect that made this endface attractive means for light coupling improvement is that its shape matches the elliptical shape of the laser diode spot [25]. This feature allows more light to be coupled into the fiber and at the same time improves the alignment tolerance between the laser diode and the fiber. Fig. 11 shows SEM photograph of wedged endface profile.

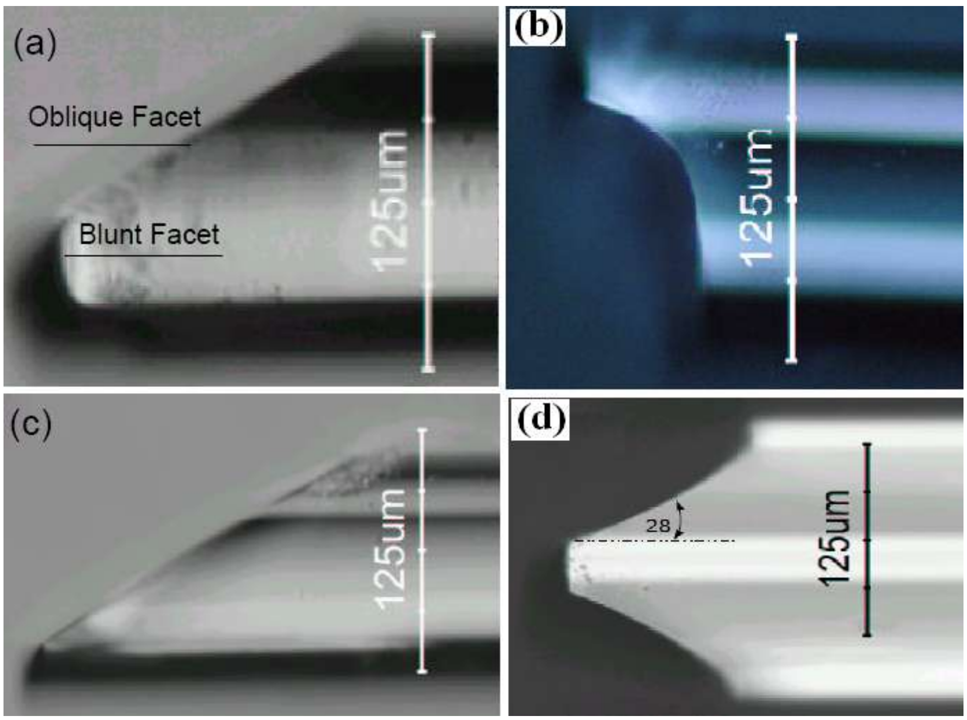

Fig 10. Different optical fiber endfaces profile made using NGM a) oblique profile, b) D-shaped profile, c) slant profile, and d) wedged profile.

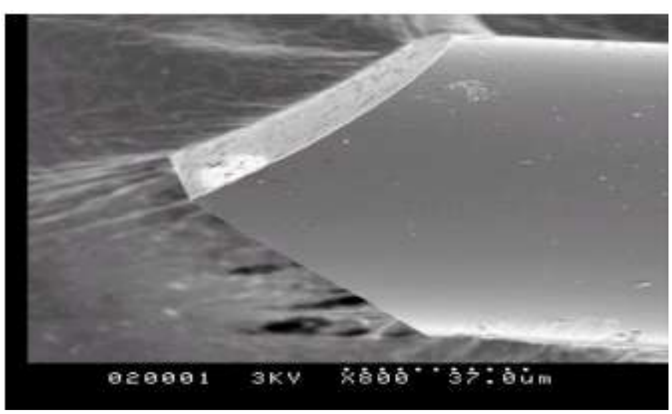

Fig. 11. SEM photograph of wedge fiber endface

VI. Scope and limitations

The NGM used in this work could be used to grind almost any kind of brittle material and therefore the prospects of using this machine are almost endless. The machine however, is limited so far by its inability to directly produce spherical lenses. An additional precise and controllable rotational motion is required for the feeding stage in order to be able to produce curved profiles.

VII. Conclusion

This paper presented results of an extensive investigation to determine the critical depth of cut for ductile material removal of optical fiber material, suitable grit size, grinding speed and in-feed rate required to obtain optical surface quality free from surface or sub-surface damages. The study revealed that AngstromLap^{TM} films with grit sizes of 1.0 μm can be used to ensure ductile mode material removal. The average surface roughness achievable using these grinding parameters was 4 nm.

It has been also demonstrated in this paper that it is possible to fabricate variety of optical fiber endfaces using nano-grinding technique. The flexibility and the easiness by which the nano-grinding machine can be reconfigured to produce different endface geometries have also been demonstrated. For example it has been shown that it is as easy to fabricate conical lens with internal angle of 68° as it is to fabricate conical lens with an internal angle of 90°, or any oblique endface for that matter.

The type of lenses that could be produced with this technique can be extended to include spherical lenses. This can be achieved by using Loose Abrasive Basting (LAB) technique reported by the author elsewhere [28]. It would be interesting if the NGM could be modified in such a way to allow for the direct fabrication of spherical lenses.

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