Application of Ultrasonic Assisted Machining Technique for Glass-Ceramic Milling

S. Y. Lin, C. H. Kuan, C. H. She, W. T. Wang

***Abstract*—**In this study, ultrasonic assisted machining (UAM) technique is applied in side-surface milling experiment for glass-ceramic workpiece material. The tungsten carbide cutting-tool with diamond coating is used in conjunction with two kinds of cooling/lubrication mediums such as water-soluble (WS) cutting fluid and minimum quantity lubricant (MQL). Full factorial process parameter combinations on the milling experiments are planned to investigate the effect of process parameters on cutting performance. From the experimental results, it tries to search for the better process parameter combination which the edge-indentation and the surface roughness are acceptable. In the machining experiments, ultrasonic oscillator was used to excite a cutting-tool along the radial direction producing a very small amplitude of vibration frequency of 20KHz to assist the machining process. After processing, toolmaker microscope was used to detect the side-surface morphology, edge-indentation and cutting tool wear under different combination of cutting parameters, and analysis and discussion were also conducted for experimental results. The results show that the main leading parameters to edge-indentation of glass ceramic are cutting depth and feed rate. In order to reduce edge-indentation, it needs to use lower cutting depth and feed rate. Water-soluble cutting fluid provides a better cooling effect in the primary cutting area; it may effectively reduce the edge-indentation and improve the surface morphology of the glass ceramic. The use of ultrasonic assisted technique can effectively enhance the surface finish cleanness and reduce cutting tool wear and edge-indentation.

***Keywords*—**Glass-ceramic, ultrasonic assisted machining, cutting performance, edge-indentation.

I. Introduction

PROGRESS of science and technology, and development of industrial production, the use performance requirements of machinery product and its assembly components are asked for better quality day by day. On relatively, the needs of the raw material must have high hardness, high functionality, high thermal strength, high temperature resistant, able to withstand complex stress and corrosion resistance, etc. A variety of new materials are emerging for these demands. Among them, many are hard and brittle materials, silicon wafers, glass, ceramics are a typical representative. Glass-ceramic is a kind of combination of glass phase and crystal phase composite materials with high mechanical strength, good insulation, wear resistance, corrosion resistance, high thermal stability characteristics, etc. Its good high temperature performance has been widely used in rocket engines, aviation aircraft and other aircraft heat resistance parts. Glass-ceramic combines the advantages of glass and ceramics, and it owns an excellent performance that metal materials are difficult to achieve. This superior property makes it suitable for high corrosion resistance, and poor working environments, such as severe high strength-related parts. Currently, glass ceramics are widely used in medical equipment, machinery manufacturing, automotive, defense technology, optics, precision instruments, electronics and microelectronics, aerospace, chemical and industrial architectures, etc.

Stephenson et al. [1] investigated ELID grinding of BK7 glass and Zerodur using acoustic emission for state detection. The performance of ELID grinding with a cast iron bond wheel was evaluated and the result was compared to that grinding with a resin bond wheel without ELID. Correlations between the electrical dressing parameters and the detected AE signals were observed. Results show that the AE sensing technique is an effective method for monitoring an ultra precision grinding process for the condition of the grinding wheel identification and the mechanism of ELID grinding investigation. Li et al. [2] introduced rotary ultrasonic machining (RUM) into drilling holes on ceramic matrix composites (CMC) panels and investigated the feasibility to machine CMC. Cutting forces and material removal rates (MRR) are compared for machining of CMC with and without ultrasonic vibration and for two types of CMC materials and one type of ceramic material (alumina). Chippings at the hole exit by RUM process were also discussed. The cutting force can be reduced and MRR can be improved with RUM as compared with diamond drilling process. The results obtained show that spindle speed and feed rate, and their interaction, have significant effects on hole quality. Lee et al. [3] introduced an ultrasonic machining method into micro-grooving on brittle materials such as planar lightwave circuits (PLCs) and glass by using a polycrystalline diamond tool, and the cutting characteristics were thus investigated. They built the machining system with an ultrasonic vibration tool which was in turn used for micro-grooving experiments of these two workpiece materials. The results show that better groove shapes with low chipping of PLCs and glass were obtained by the two-dimensional ultrasonic vibration cutting. Lohbauer et al. [4] assessed the fracture strength of a glass ceramic and of a resin composite as a function of surface roughness. They also related the strength data to flaw sizes, microstructural and fractographic examinations. Cutting, grinding and polishing techniques were used to generate different surface roughness levels. The four-point bending and Weibull statistics were used for fracture strength measurement

S. Y. Lin is with the National Formosa University, Yunlin 63201 Taiwan (corresponding author to provide phone: +886-5-6315319; fax: +886-5-6315310; e-mail: sylin@nfu.edu.tw).
C. H. Kuan and C. H. She are with the Mechanical and Computer-Aided Engineering Department, National Formosa University, Yunlin 63201 Taiwan (e-mail: onlyone78526@yahoo.com.tw, chshe@nfu.edu.tw).

and analysis, respectively. Indentation fracture method was used to calculate fracture toughness. The results show that fracture strength is decreased as the surface roughmess is decreased either for glass ceramic or for resin composite. Zhong [5] proposed a ductile and partial ductile mode for performing machining of silicon, glass and some high-class ceramics. Using partial ductile-mode grinding and ductile-mode polishing are successfully applied to manufacturing aspherical glass lenses. The presence of ductile streaks results in the reduction of polishing time and improvement of surface quality.

Hardened and brittle material such as glass-ceramic has gradually become the important material for precision instruments, aerospace and defense technology industry applications in recent years. In which bio-medical application is particularly active. As its demand is increased constantly, various requests on machining qualities of glass-ceramic are also more stringent. At present, the main machining ways on glass-ceramic are almost with grinding or engraving milling and these machining processes are too complicated and too much wasted. Therefore, seeking a breakthrough for shortening the process and saving the cost effectively is an important issue for the machining workers. Because glass-ceramic with high strength, high hardness, high brittleness, low thermal conductivity and hence low machinability, it causes the cutting-tool wear quickly during the machining process. Also, the crack and edge-indentation are easily induced on the machined surface and outer edge, respectively. In order to solve the above problems, this study applies the diamond-coating cutting tool to conduct glass-ceramic machining through a combination of an ultrasonically assisted machining system and different cutting fluids under the conditions of high cutting speed, low depth of cut and suitable feed rate. It is expected to handle the ductile-brittle transition mode properly for glass-ceramic machining and enhance the processing efficiency, improvement of surface quality and reduction of production cost consequently.

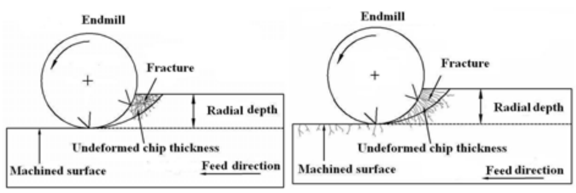
II. Theoretical Foundation

A. Structure and Properties of Glass Ceramics

Glass-ceramic is fabricated through a hot melting, forming, heat treatment procedures, it is a kind of combination of glass phase and crystal phase composite materials with high mechanical strength, good insulation, wear resistance, corrosion resistance and high thermal stability characteristics. The most prominent feature of glass ceramics is available for those standard processing tools and equipments used in metal machining such as turning, milling, planing, grinding, sawing, cutting and tapping and other processing. The processing performance of micro-crystallite glass ceramic is similar to cast iron, which can be machined into a variety of complex shape and high precision products. Although the micro-crystallite glass-ceramic is a brittle material, the general tolerance levels can be controlled at IT7 level, clearness can be of 0.5 μ and accuracy can be of 0.005 mm as long as its processing methods and processing parameters are reasonably determined. As for excellent equipment and skilled operatives, the accuracy may up to be μ level.

B. Brittle Materials Machining Mechanism [6]

In side cutting with an up-milling orientation, the undeformed chip thickness varies from zero at the beginning of cut to a maximum value near the end of cut. In milling process of brittle material, if the increasing undeformed chip thickness reaches the critical value for ductile-brittle transition at some point between the beginning and the end of cut, brittle fracture takes place at that point. If the point of brittle fracture is sufficiently far from the plane of final machined surface, brittle fracture will be removed by the cutting action of the subsequent cutting edge and the final machined surface will be fracture free as depicted in Fig. 1 (a). Conversely, if the brittle point is too close to the plane of final machined surface, fracture region will extend beyond the cutting chip and reach the area below the level of the final machined surface. This result in undesirable formation of cracks beneath the finished surface, which is commonly regarded as a brittle-mode machined surface as shown in Fig. 1(b). The maximum undeformed chip thickness achieved in milling is dominated by the feed per edge and radial cutting depth. The occurrence point of brittle fracture is strongly affected by the feed per edge. A smaller value of the feed per edge postpones the occurrence of brittle fracture and is helpful to ductile-mode machining, while a larger value of the feed per edge causes the fracture to take place close to the final machined surface. In fact, a higher value of the feed per edge is favored. Therefore, it is a hard task to enhance the feed per edge without reaching the critical point of brittle fracture.



(a) Smaller feed per edge (b) Larger feed per edge

Fig. 1 Fracture formation and propogation in a side-milling of the hard-brittle materials

C. Ultrasonic Assisted Machining Technique

In the glass-ceramic cutting processes, high temperature is promptly accumulated around the cutting edge due to the contact between the workpiece material and cutting-tool, and the very poor thermal conductivity of the workpiece material itself. In order to improve this phenomenon, cutting fluid should be used for cooling and lubrication to ensure good cutting performance. But if the cutting fluid is simply applied for high temperature cooling, the actual improvement results are limited. By introducing an ultrasonic assisted cutting technique, a vacuum region may be constituted around the primary cutting zone and the pumping effect is formed in this area, which may enhance the cutting fluid penetrating into the cutting zone accelerating high temperature cooling at the tool-tip. Furthermore, ultrasonic assisted cutting technique may convert the engagement type of cutting tool-chip into an interaction manner of a small amount of vibration. The results obtained from the literature have also reported that the following effects may be induced if the ultrasonic assisted machining technique is properly introduced in the cutting process, i.e., to improve the bur generation around the machined side surface, reducing cutting forces and thus improve the vibration effects arising from the cutting, to improve the quality of the surface roughness, to reduce friction at tool-workpiece interface, increasing tool life and reducing the geometrical accuracy error. Thus, appropriate application of ultrasonic assisted technique in cutting process can actually improve the cutting performance. A model combines ultrasonic assisted cutting technique and cutting fluid is schematically shown in Fig. 2.

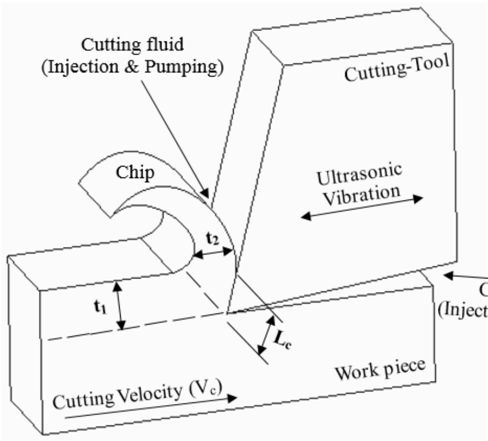


Fig. 2 Schematic cutting model for combination of ultrasonically assisted machining and cutting fluid

III. Experimental Approach ATH

Side-milling experiment with the assistance of ultrasonic vibration on glass-ceramic workpiece material is performed in this study. The process parameters are selected by reading the related articles in literatures which side-milling parameters for hard-brittle materials under different working conditions were referred. The cutting performance is investigated under the conditions of various ways of cooling/lubrication conditions such as the use of water-soluble cutting fluid and of MQL. Furthermore, the variations of edge-indentation, cutting-tool wear, machined surface roughness and surface morphology of the glass ceramic material are compared mutually whether if an ultrasonic assisted machining technique is used or not.

In this study, full-factorial experiments are conducted with the variables and conditions consisting of three levels of cutting speed, three levels of feed rate, three levels of radial depth of cut, and two options of cutting fluid (water-soluble and MQL), totally 54 combinations (3×3×3×2 = 54) are constituted in this study. The axial depth of cut was set as the thickness of the workpiece material. The process parameter planning for side-milling experiments is shown in Table I while the experimental set-up related to equipments and instruments is shown in Fig. 3. The experimental results are used to investigate the variations of edge-indentation, cutting-tool wear, machined surface roughness and surface morphology of the glass ceramic material under various combinations of the process parameters and cooling/lubrication conditions with an ultrasonic assisted machining technique.

TABLE I
Process Parameter Planning for Side-Milling Experiments

Process parameter	Setting
Cutting-tool diameter	ψ6mm
Cutting speed	V=565, 754, 942m/min
Feed rate	F=150, 200, 250(mm/min)
Radial depth of cut	a_e=3, 5, 7μm
Axial depth of cut	a_p=2 mm
Cutting fluid	water-soluble: 5% concentration MQL: pressure: 0.6MPa, nozzle-tool distance: 80mm, flow rate: 50ml/h

Workpiece material used in this study is a machinable glass ceramic block which geometrical size is 100×100×2mm. A three edge end mill of the tungsten carbide with diamond coating was used as a cutting-tool. Lubricant is CASTROL CARECUT ES1 biodegradable cutting oil ester oil. A motor spindle is used to enhance the cutting speed and its maximum rotational speed can be up to 50,000rpm.

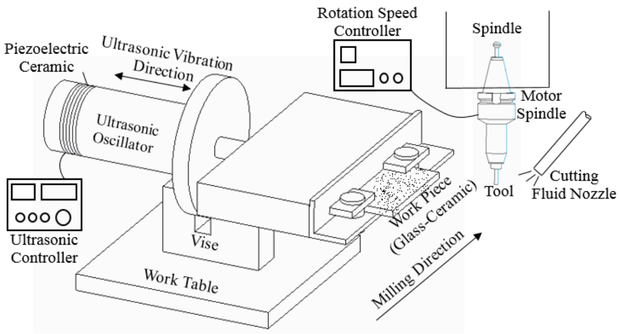


Fig. 3 Experimental set-up for glass ceramic workpiece side milling

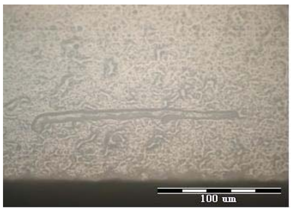
IV. Results and Discussion

A. Influence of Ultrasound Assisted Cutting Technique

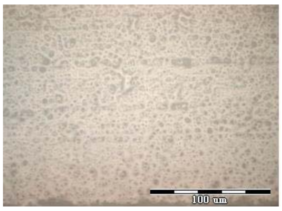
Firstly, milling experiments of glass ceramic were conducted with or without the assistance of ultrasonic vibration, respectively, and their results are compared to each other to validate the effect of ultrasonic assisted cutting. Table II shows a comparison of edge-indentation and cutting tool wear under the conditions of V=754 m/min, a_e=3μm and without UAM. Edge-indentation and cutting tool wear were measured by microscope off-line. Fig. 4 shows the comparison of the machined surface morphology for the use of MQL with or without ultrasound assisted cutting, respectively. Fig. 5 shows the comparison of edge-indentation and cutting-tool wear versus feedrate for the use of water soluble with or without ultrasonic assisted cutting, respectively. The results show that using UAM can indeed reduce the edge-indentation in glass ceramic machining, and the surface brightness and surface craters have a better improvement situation, and these reductions can be from about 9% to 15%.

TABLE II
COMPARISON OF EDGE-INDENTATION AND CUTTING-TOOL WEAR UNDER THE CONDITIONS OF V=754 M/MIN, A_E=3MM AND WITHOUT UAM.

No.	F(mm/min)	Edge-indentation (μm)		Too wear (μm)	
		WS	MQL	WS	MQL
1	150	25.34	33.85	69.75	80.11
2	200	27.63	34.12	75.33	60.32
3	250	30.11	35.97	85.7	65.43

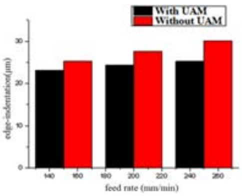


(a) without UAM

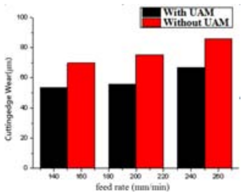


(b) with UAM

Fig. 4 Comparison of surface morphology between with and without UAM for the use of MQL



(a) edge-indentation vs F

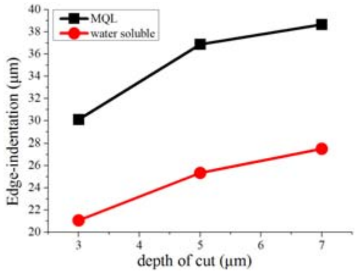


(b) cutting-tool wear vs F

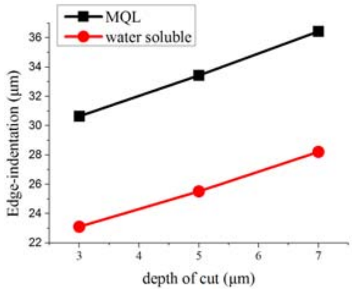
Fig. 5 Comparison of edge-indentation and cutting-tool wear versus feedrate for the use of water soluble with or without UAM, respectively

B. The Effect of Radial Depth of Cut on Edge-Indentation

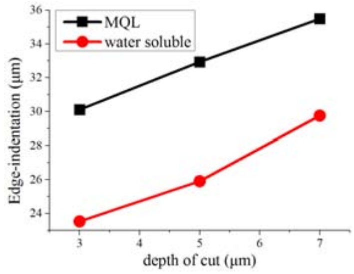
Fig. 6 shows the relationship between edge-indentation and radial depth of cut under different cutting fluids, cutting speeds and f=150mm/min. Radial cutting depth has a greater impact effect on machined surface edge-indentation. As the cutting depth is increased, a more obvious mark of edge-indentation and chipping phenomenon induced on machined surface. This is due to the increase in undeformed chip thickness, and the stresses induced in plastic and elastic deformation zones become greater. As the critical cutting force is attained, the cracks will be formed at the bottom of the plastic zone and propagated to a certain depth. According to the results obtained, a combination of low cutting speed, low depth of cut and low feed rates is helpful to improve the quality of edge-indentation in glass ceramic milling. Besides, water soluble has a significant improvement result on edge-indentation suppression due to its flooded pour action causing the primary cutting zone cooling.



(a) V=565 m/min



(b) V=754 m/min

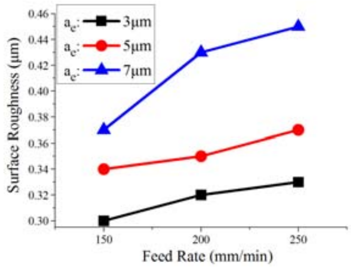


(c) V=942m/min

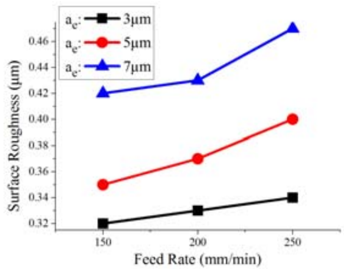
Fig. 6 Relationship between edge-indentation and radial depth of cut under different cutting fluids, cutting speeds and F=150mm/min

C. Surface Roughness

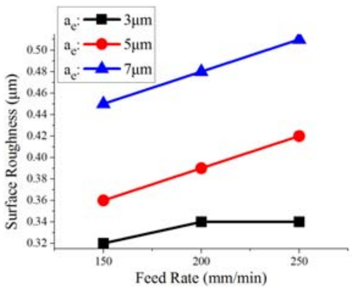
Fig. 7 shows the relationship between surface roughness and feed rate under different radial depths of cut, cutting speeds and water soluble cutting fluid via a flooded pour way. As the level of cutting speed, depth of cut and feed rate is increased, the surface roughness is also increased. The cutting heat is promptly accumulated around the cutting edge as the level of each process parameter is increased. If an effective cooling cannot be imposed on cutting-tool in-time, the cutting edge may be getting softer and the sustainable ability of cutting load is thus reduced resulting in worse surface roughness.



(a) V=565m/min



(b) V=754m/min



(c) V=942m/min

Fig. 7 Relationship between surface roughness and feed rate under different radial depths of cut, cutting speeds and water soulble flooded pour cutting fluid

D.Ductile Cutting Mode of Glass Ceramic

Fig. 8 shows the continuous chips in glass ceramic milling process. Under the conditions of n=50,000rpm, F=200mm/min, a_e=3 or 5μm and the use of water-soluble, the continuous chips were found in glass-ceramic milling experiments. The maximums chip thickness is about 3.81μm and 5.93μm corresponding to the case of a_e=3μm and a_e=5μm, respectively. But when a_e is up to 7μm the continuous chip is not appeared. It is inferred that the former two cases are under ductile cutting mode while the latter one is under brittle cutting mode.

(a) a_e=3μm (b) a_e=5μm

Fig. 8 The continuous chips in glass ceramic milling

V. Conclusion

In this study, glass-ceramic milling experiments are performed with ultrasonic assisted machining technique. The cutting performance such as edge-indentation, machined surface morphology and roughness, and cutting-tool wear are investigated for different combinations of process parameters and two cooling/lubrication conditions of water-soluble and MQL. From the above analysis, the following conclusions can be drawn.

1. Under the conditions of V=565m/min, F=150mm/min, a_e=3μm and the use of water-soluble, the smallest edge-indentation is obtained as 21.06μm. While under the conditions of V=942m/min, F=150mm/min, a_e=3μm and the use of MQL, the smallest edge-indentation is obtained as 30.11μm.
2. Flank wear is a major wear mode for glass-ceramic milling in this study. Flank wear is increased as the level of cutting speed, cutting depth and feed rate is increased. Under the conditions of V=942m/min, F=250mm/min, a_e=7μm and the use of water-soluble, the largest flank wear is obtained as 121.59μm. While under the conditions of V=565m/min, F=200mm/min, a_e=3μm and the use of MQL, the largest flank wear is obtained as 81.9μm.
3. The use of ultrasonic assisted machining the workpiece edge-indentation can reduce about from 9% to 15% and the cutting-tool wear can reduce about from 3% to 20%.
4. Under the conditions of n=50,000rpm, F=200mm/min, a_e=3 or 5μm and the use of water-soluble, the continuous chips were found in glass-ceramic miling experiments. The maximums chip thickness is about 3.81μm and 5.93μm corresponding to the case of a_e=3μm and a_e=5μm, respectively. But when a_e is up to 7μm the continuous chip is not appeared. It is inferred that the former two cases are under ductile cutting mode while the latter one is under brittle cutting mode.

References

[1] D. J. Stephenson, X. Sun, C. Zervos, "A study on ELID ultra precision grinding of optical glass with acoustic emission," Int. J. Mach. Tools Manuf., vol. 46, pp. 1053-1063, 2006.
[2] Z. C. Li, Y. Jiao, T. W. Deines, Z. J. Pei, C. Treadwell, "Rotary ultrasonic machining of ceramic matrix composites: feasibility study and designed experiments," Int. J. Mach. Tool. Manu., vol. 45, pp. 1402-1411, 2005.
[3] J. S. Lee, D. W. Lee, Y. H. Jung, W. S. Chung, "A study on micro-grooving characteristics of planar lightwave circuit and glass using ultrasonic vibration cutting," J. Mater. Process. Technol., vol. 130-131, pp. 396-400, 2002.
[4] Ulrich Lohbauer, Frank A. Muller, Anselm Petschelt, "Influence of surface roughness on mechanical strength of resin composite versus glass ceramic materials," Dental Materials. vol. 24, pp. 250-256, 2008.
[5] Z. W. Zhong, "Ductile or partial ductile mode machining of brittle materials," Int. J. Adv. Manuf. Technol., vol. 21, pp. 579-585, 2003.
[6] M. Arif, M. Rahman, W. Y. San, "Analytical model to determine the critical feed per edge for ductile-brittle transition in milling process of brittle materials," Int. J. Mach. Tools Manuf., vol. 51, pp. 170-181, 2011.

Shen-Yung Lin received the Ph. D degree from National Taiwan University of Science and Technology 1991. He is currently a Professor with the Department of Mechanical and Computer-Aided Engineering at National Formosa University, Taiwan. He has published over 50 papers in international peer

reviewed journals. His research interests are in manufacture mechanics, structure design, sound and vibration, and hardened and difficult-to-cut material machining.

Chen-Hao Kuan received the MS degree from National Formosa University 2014.

Chen-Hua She is an associate professor in the Department of Mechanical and Computer Aided Engineering at National Formosa University. He received his MS and PhD degrees in Mechanical Engineering from National Cheng Kung University in 1989 and 1997, respectively. His main research interests are in the areas of multi-axis NC machining and CAD/CAM.

Wen-Teng Wang is an assistant professor in the Department of Mechanical and Computer Aided Engineering at National Formosa University. He received his bachelor and PhD degrees in Mechanical Engineering from National Taiwan University 1991 and 1996, respectively. His main research interests are in mold design & making, medical device design & manufacturing and CAD/CAM.