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Surface Engineering and Science

Surface modification technology for green tribology

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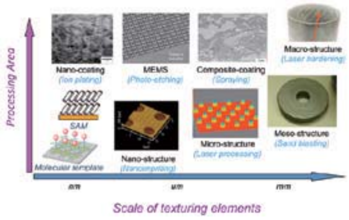
1. Introduction

The Earth is facing many serious environmental problems. Global warming and environmental pollution have been progressing constantly. How should tribology deal with these problems? How much can tribology contribute to solving these problems is a question that is often asked. Tribology has supported various technological developments over the years, such as improving the energy efficiency and durability of vehicles, household appliances, industrial machines and plants.



Continued on page 2

Search for and application of novel thin film amorphous alloys for micro-nano structures

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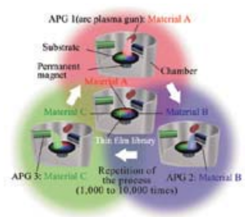
1. Introduction

Amorphous alloys were initially produced by liquid quenching in 1960, and since then, many such alloys with a wide range of compositions have been discovered and used in a multitude of applications. In recent years, bulk metallic glasses, which are a type of amorphous alloy having high amorphous formability and showing a glass transition, have become a topic of considerable interest.



Thin film amorphous alloys including metallic glasses can be used in micro-nano structures such as micro-electromechanical systems (MEMS),micro-machines and for surface modification Continued on page 4

Development of Biomimetic DLC Films using Plasma Processing and its Application to a Coronary Stent

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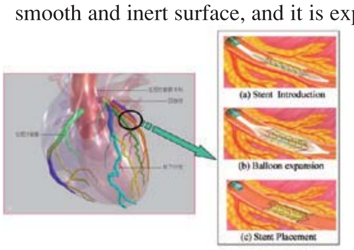
1. Introduction

Diamond-like carbon (DLC) thin films are amorphous carbonaceous films with both graphite and diamond bondings. DLC films deposited by plasma enhanced chemical vapor deposition methods have very smooth and inert surface, and it is expected as one of the biocompatible coatings for the surface of medical device avoiding any thrombosis formation. As for the medical device,most of the components were made of combination of various materials such as.



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Novel laser applications to 3-D micromachining and high-resolution measurement for micro/nano-manufacturing

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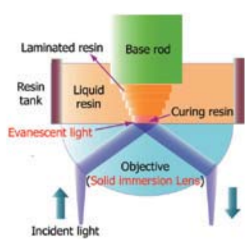
1. Introduction

For next-generation micro/nano-manufacturing process, light energy on an engineering surface can still play an important role as the machining energy and the energy of active measurement. Because light has many unique intrinsic properties, such as spatial transmission, broad band spectrum, and high controllability of its physical values of frequency, amplitude, phase, polarization, and so on, allowing non-conventional machining and non-destructive measurement.



The purpose of our research is to develop new types of laser-applied 3-D micro fabrication and nano Continued on page 8

Surface modification technology for green tribology

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Continued from page 1 Tribology has also responded promptly to societal demands for decreasing substances from engineering products that would be hazardous to the environment, which has included abolishing asbestos from vehicle brake systems, replacing refrigerants with CFC-substitutes, and controlling the lead used in bearings. As societies aim to become sustainable, green tribology needs to be involved and contribute to the solution more than ever before. Surface modification, such as surface texturing and coating, is one of the most important key technologies for advancing green tribology for sustainable societies.

2. Multi-scale surface texturing

Multi-scale surface texturing is a new concept of surface modification for tribo-materials. Making use of the tribological phenomenon that becomes predominant at each scale level, multi-scale surface texturing aims at improving the total performance inclusively by architecting the surface structure on a consecutive scale from the nano-micro level to the macro level. Figure 1 shows a variety of surface structures and the processing related to the size of the texturing element and processing area. It starts from molecular modification on the surface using super molecules and self-assembled monolayers (SAMs), and there are various processing methods such as nano-particle and/or multi-layer composite coatings, nano-imprinting, MEMS, sandblasting, laser ablation, precision machining and laser hardening. It will be very important in the future to create the multi-scale surface texture by combining two or more of these processing methods.

Figure 2 shows an example of improving the sliding characteristics by surface texturing1). As for water lubrication of ceramics, this application has been sought for about 20 years with the discovery of a low-friction phenomenon. However, it has not seen wider use due to the problematic frictional property in the low sliding speed region. Micro-laser processing has also been adapted for forming dimple patterns on silicon nitride surfaces to improve the friction characteristics. The range of the hydrodynamic lubricating condition was shifted to a small bearing characteristic number region of higher load and lower sliding velocity. This expansion of the hydrodynamic lubrication range is thought to have been achieved on medium-sized dimple structures which generated higher hydrodynamic pressure and protected the sliding surface from abrasive damage by the wear particles. However, many uncertainties remain with regard to the hydrodynamic pressure generation mechanism on textured surfaces. It is expected that a design manual will be created for optimizing multi-scale surface textures by applying the computational fluid dynamics (CFD) method.

3.DLC coatings for green lubrication

Diamond like carbon (DLC) coating technology has advanced remarkably in the last 10 years. DLC coatings, which have some tribological advantages with their high hardness, surface smoothness and chemical stability, are already being applied as low frictional tribo-materials to some automobile and industrial machine parts. Additionally, DLC films are chemically inert, a property that is expected to be utilized for controlling the decomposition of the lubricant on the sliding surface2).

Ionic liquids have received attention for their use as environmentally friendly solvents (green chemistry). Recently, ionic liquids are expected to see use as a novel lubricant3) because they have unique properties that include non-volatility, thermal stability and electrical

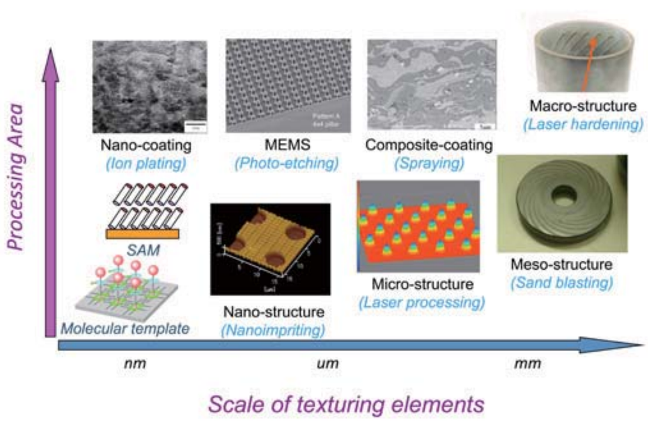

Figure 1 Multi-scale surface texturing

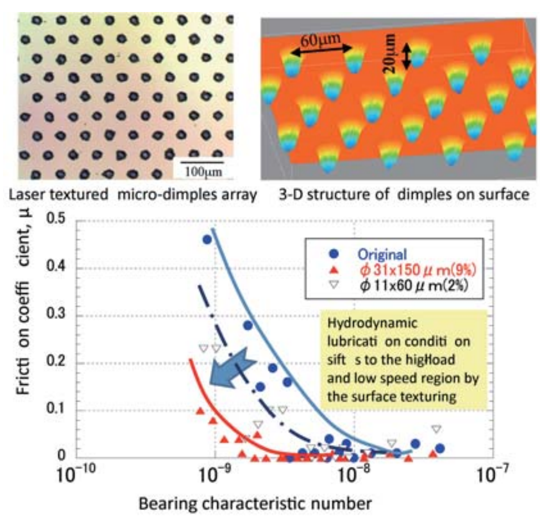

Figure 2 Water lubrication of surface-textured ceramics

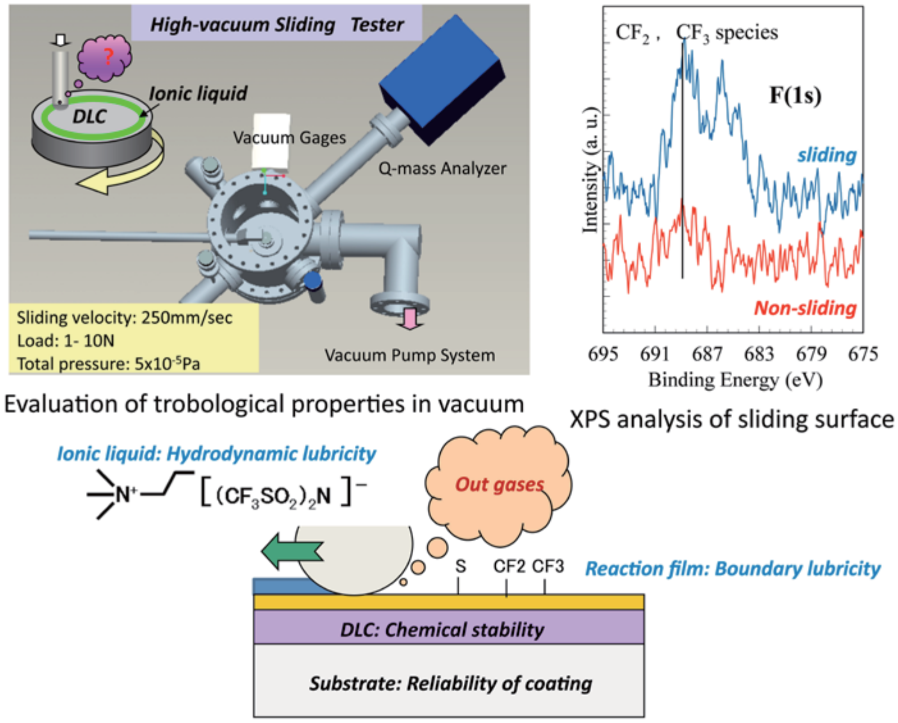

Figure 3 Lubricity of ionic liquid for DLC

polarity. By combining each of the advantages of ionic liquids and DLC coatings, we have started to develop a novel tribo-system for high-vacuum sliding applications4). We evaluated the tribological properties of DLC coatings under lubrication with an ionic liquid using a high-vacuum pin-on-disc sliding tester. During the sliding tests, we used a Q-mass analyzer to monitor the friction coefficient and the residual gases as shown in Fig. 3. The ionic liquid exhibited stable friction coefficients compared with dry sliding. XPS analytical results revealed that S and F elements were present on the sliding surface compared with non-sliding surface. We think that the lubricity of the ionic liquid depends on the tribo-chemical reaction product between the ionic liquid and the DLC sliding surface. On the other hand, the tribo-chemical reaction on the sliding surface causes gas generation with the decomposition of the ionic liquid molecules. There was not much gas emission, and the influence on the total pressure was slight. It is very important to control a moderate tribo-chemical reaction that balances the lubricity and the emission of the decomposition gases by selecting the kind of ionic liquid and the combination of the ionic liquid with the tribo-materials.

Vegetable oil, which has been used as a lubricant from ancient times, is a representative green lubricant that is carbon neutral, biodegradable and safe for human health. However, it is hardly used now because its anti-oxidation and durability performance are inferior to mineral oils and synthetic oils. Recently, the wider use of DLC as a tribo-material has brought about the possibility of using vegetable oil as a lubricant. Triacylglycerol contained in vegetable oil is understood to have excellent lubricity for DLC. Moreover, DLC features corrosion resistance while the oxidation of the vegetable oil is controlled on the chemically inert sliding surface of the DLC. Such a green lubrication system is expected to see use in food machines.

4.Conclusion

The global warming problem has reached a point at which action cannot be delayed. The Japanese government has announced a challenging target: by 2020 reduce greenhouse gas emissions by 25% compared with 1990. To achieve such a high objective, it is necessary not only to expect novel technological development but also to create realistic solutions by extending conventional technologies. Green tribology, through progress in surface modification, is seen to be an effective engineering technology that can contribute very much to sustainable societies.

References

1) H. Yamakiri et al., “Laser surface texturing of silicon nitride under lubrication with water”, Tribology International (to be published)
2) T. Saito, “Vacuum clean lubricant film V-DFO”, NSK Technical Journal, Vol.673, 22–25 (2002)
3) H. Kamimura et al., “Effect and mechanism of additives for ionic liquids as new lubricants”, Tribology International, 40,620–625 (2007)
4) Yagi et al., ” Lubricity and chemical reactivity of ionic liquid used for sliding metals under high-vacuum condition”, Proc. IMechE Vol. 223 Part J: J. Engineering Tribology (in press)

Search and application of novel thin film amorphous alloys for micro-nano structures

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Continued from page 1 of precise dies. To develop applications of thin film amorphous alloys, the author has been carrying out a broad investigation, ranging from composition search to micro-fabrication methods for the materials, from the point-of-view of mechanical engineering. In this report, an outline of the study and application of a novel thin film amorphous alloy for micro-nano structures is introduced.

2. THIN FILM METALLIC GLASSES FOR MEMS

The author has been studying a new MEMS material, thin film metallic glass (TFMG)[1]. Figure 1 shows the characteristics of this material. In order to apply the metallic glass to MEMS, the author successfully fabricated TFMGs using an RF-magnetron sputtering method, and has reported their thermal, mechanical and electrical properties[2].

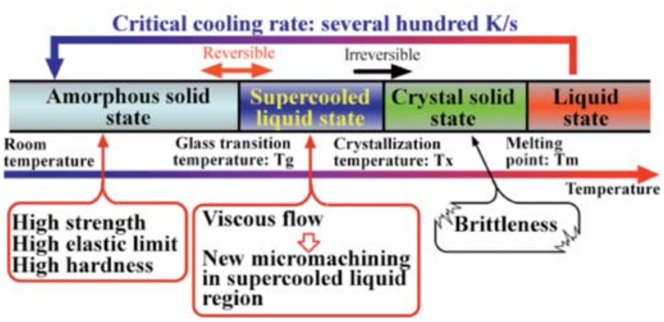


Fig. 1 Characteristics of metallic glass

A Pd-based ($Pd_{76}Cu_7Si_{17}$, atomic %) TFMG is mainly employed in this study. Table 1 shows the properties of this TFMG, compared to those of polysilicon and stainless steel. The TFMG exhibits an elastic limit higher than that of both polysilicon and stainless steel. The TFMG is also a homogeneous and isotropic material; hence, it is free from defects which are inevitable in crystalline structures. The TFMG softens and undergoes viscous flow in a certain temperature range called the supercooled liquid region (SCLR), which allows for three-dimensional microforming[3].

Three-dimensional microformed TFMG can be employed for moving parts in out-of-plane motion microactuators through the use of its own large elastic deformation. Using the properties of this TFMG, we have developed several new microactuators having three-dimensional structures that allow for out-of-plane motion , as shown in Fig. 2.

(a)Electrostatic-driven micro-lens actuator for a high capacity magneto-optical disk drive[4],

(b)Two-degrees-of-freedom (2-DOF) microactuator that is actuated by PZT films[5],

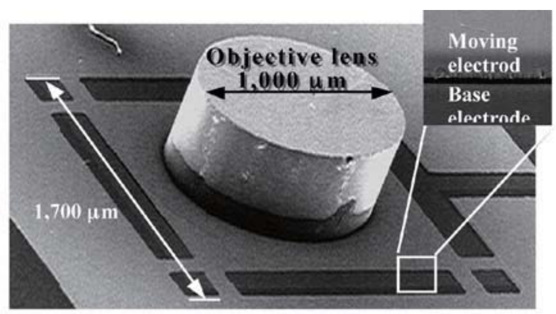
(c)Integrated conical spring linear actuator (CSLA) capable of large stroke motion vertical to the substrate by electrostatic force[6],

(d)Out-of-plane analog motion microactuator that has

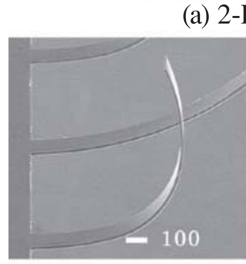
Table 1 Properties of TFMG and other materials

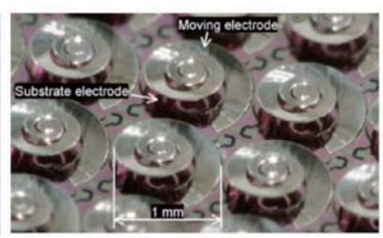
	Pd-based TFMG ($Pd_{76}Cu_7Si_{17}$)	Polysilicon	Stainless steel (SUS304)
*Tg, Tx, Δ Tx	637 K, 669 K, 32 K	—	—
Young's modulus E	57.9 GPa	170 GPa	197 GPa
Tensile strength σ	1.14 GPa	1.21 GPa	0.5 GPa
σ / E	0.020	0.007	0.003
Elastic limit (strain%)	1.97 %	0.71 %	Less than 0.2 %
Hardness	Hv 515.0	N.A.	Hv 540
Density	10.42x10^3 kg/m^3	10.42x10^3 kg/m^3	10.42x10^3 kg/m^3

*Tg: glass transition temperature
Tx: crystallization temperature
ΔTx (=Tx-Tg): supercooled liquid region

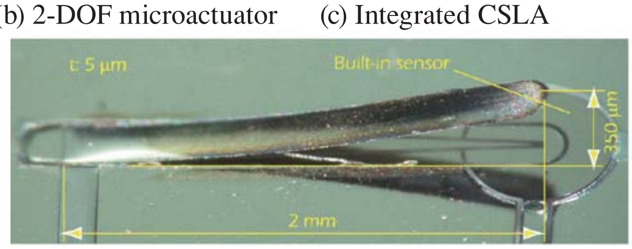


(a) 2-DOF microactuator





(b) 2-DOF microactuator (c) Integrated CSLA



(d) Analog motion microactuator

Fig. 2 Three-dimensional microactuators made of TFMG full-range stabilization without pull-in effect[7].

3. COMBINATORIAL APPROACH FOR NOVEL THIN FILM AMORPHOUS ALLOYS

In order to realize novel thin film amorphous alloys including TFMG for various types of applications, a new combinatorial method to deposit thin films using arc plasma (Combinatorial Arc Plasma Deposition; CAPD) has been studied[8)]. The CAPD setup includes three arc plasma guns (APGs), with each gun shooting a pulse-like plasma of the component elements of the alloy system to be searched, in order to deposit a compositionally-graded thin film on an alumina substrate. Figure 3 shows the concept of CAPD.

The deposited thin film is separated into 1,089 (33x 33) samples (each with a size of 1x1 mm^2), and each is numbered using 5-bit row and column marks to indicate the sample's position on the substrate. This sample group is referred to as the thin film library, as shown in Fig. 4.

In the combinatorial approach, the choice of evaluation method is also important for efficiently searching through the library for an alloy with the required properties. Thickness, phase and composition can be measured automatically using commercial equipment such as a white light interferometer, an imaging-plate X-ray diffractometer (IP-XRD) and an energy dispersive X-ray fluorescence spectrometer (EDX), respectively. The complete distribution of composition and phase within the library can be efficiently determined within 2-3 weeks, as shown in Fig. 5.

However, the samples in the library are too small to accurately evaluate properties such as crystallization temperature (Tx), glass-transition temperature (Tg) and tensile strength by conventional methods. Therefore, for certain candidate samples, larger-area thin films with the same or similar compositions were deposited using a carousel-type RF magnetron sputtering system.

Since this represents a bottleneck for efficient searching, a novel library-evaluation method was also studied. The author previously reported a novel method of measuring

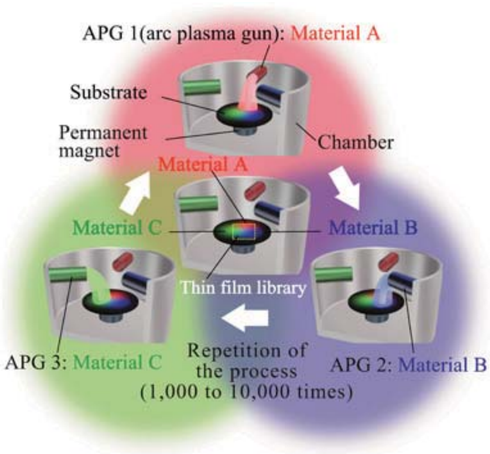


Fig. 3 Concept of CAPD

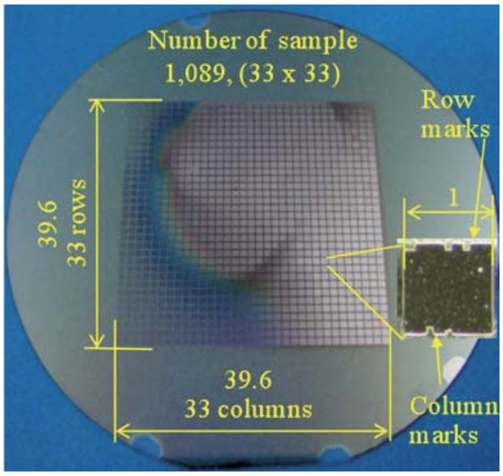


Fig. 4 Thin film library

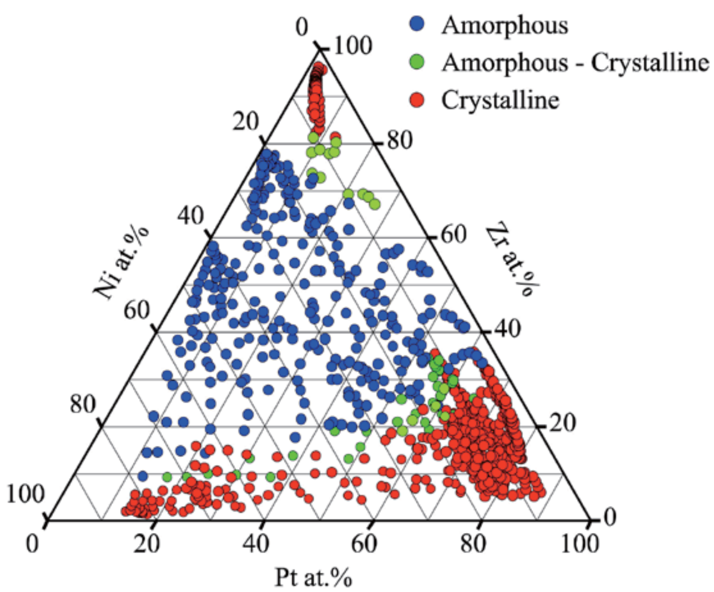
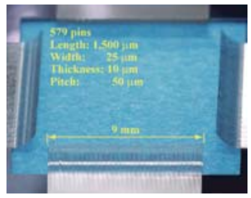
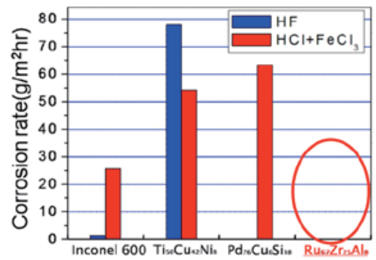
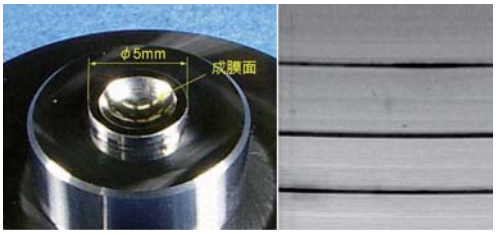


Fig. 5 Composition and phase state distribution from samples in thin film library

Table 2 Novel thin film amorphous alloys including TFMG using CAPD

Alloy	Composition and properties	Target application and notes
Lower resistivity PdCuSi TFMG[10]	$Pd_{81}Cu_5Si_{14}$ Tg: 616 K Tx: 676 K Young's modulus: 60.1 GPa Tensile strength: 1.2 GPa Resistivity: 60 $\mu\Omega\cdot$cm	Application: Integrated microprobes for investigation of LSI wafer. Note: The first test case of the novel combinatorial method using CAPD and thin film library. 
Ru-based TFMG[11]	$Ru_{65}Zr_{30}Al_5$ Tg: 902 K Tx: 973 K Young's modulus: 92.7 GPa Tensile strength: 1.89 GPa $Ru_{67}Zr_{25}Al_8$ Tg: 913 K Tx: 979 K Young's modulus: 91.0 GPa Tensile strength: 1.86 GPa	Application: High corrosion resistance vacuum sensor for LSI /MEMS process Note: The world's first discovery of Ru-based TFMG. High corrosion r esistance, good resistance to oxidation at high temperatures. 
Pt based thin film amorphous alloy[12]	$Pt_{51}Hf_{20}Zr_{17}Ni_{12}$ Tx: 942 K Young's modulus: 71.3 GPa Tensile strength: 1.08 GPa $Pt_{50}Zr_{36}Ni_{14}$ Tx: 985 K Young's modulus: 84.5 GPa Tensile strength: 2.12 GPa	Application: Optical glass lens molding die with diffractive grating Note: Thin film coated on a die blank and tooling for glass molding die 

Tx using thermography). The method determines Tx based on a change in the emissivity of thin film amorphous alloy samples, and allows a high-throughput evaluation of the small samples in the library.

By evaluation of such thin film libraries, many alloy systems with a particular set of desired properties could be efficiently searched for, and novel thin film amorphous alloys including TFMG have been selected from among many samples in the libraries. Table 2 shows examples of such novel alloys identified during the past few years.

4. CONCLUSIONS

A new method of efficiently searching for novel thin film amorphous alloys including TFMG for micro-nano structures was introduced. The method uses a combinatorial approach, and was shown to be effective in quickly identifying alloys with a desired set of properties for particular applications. Future research will focus on applying MEMS technology to the combinatorial evaluation method.

REFERENCES

1) S. Hata, K. Sato and A. Shimokohbe, Proceedings of SPIE International Symposium on Microelectronics and Micro-Electro-Mechanical Systems MICRO/MEMS'99, 3892, Queensland, Australia, pp. 97-108.(1999)
2) Y. Liu, S. Hata, K. Wada and A. Shimokohbe, Jpn. J. Appl. Phys., Vol.40, pp. 5382-5388. (2001)
3) S. Hata, J. Sakurai and A. Shimokohbe, Technical Digest of The 18th IEEE International Conference on MEMS 2005, Miami, USA, pp. 479-482.(2005)
4) S. Hata, Y. Yamada, J. Ichihara and A. Shimokohbe, 2002, Technical Digest of The 15th IEEE International Conference on MEMS 2002, Las Vegas, USA, pp. 507-510.
5) S. Hata, H. W. Jeong and A. Shimokohbe, Proceedings of European Society for Precision Engineering and Nanotechnology (euspen Glasgow 2004), Glasgow, Scotland, pp. 9-10. (2004)
6) Seiichi Hata, Tokokazu Kato, Takashi Fukushige and Akira Shimokohbe, Microelectronic Engineering, 67-68, 574-581(2003)
7) T. Fukushige, S. Hata, and A. Shimokohbe, IEEE/ASME Journal of Microelectromechanical Systems, 14, [2], 243-253 (2005)
8) Seiichi HATA, Ryusuke YAMAUCHI, Junpei SAKURAI and Akira SHIMOKOHBE, Jpn. J. Appl. Phys., 45, [4A], 2708-2713 (2006)
9) S Seiichi Hata, Yuko Aono, Junpei Sakurai and Akira Shimokohbe, Applied Physics Express, Vol. 2, No. 3, 036501 (2009)
10)Ryusuke Yamauchi, Seiichi Hata, Junpei Sakurai and Akira Shimokohbe, Jpn. J. Appl. Phys., 45, 5911-5919 (2006)
11)Junpei Sakurai, Seiichi Hata, Ryusuke Yamauchi and Akira Shimokohbe, Jpn. J. Appl. Phys. 46, 1590-1595 (2007)
12)Junpei Sakurai, Seiichi Hata, Ryusuke Yamauchi and Akira Shimokohbe, J. Solid Mechanics and Mat. Eng., 3, 1022-1032, (2009)

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Development of Biomimetic DLC Films using Plasma Processing and its Application to a Coronary Stent

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Continued from page 1 But most of medical materials have a problem related with biocompatibility when they were recognized as foreign substances in human body. A coronary stent mounted on a balloon catheter is delivered to a coronary artery to open blood vessel occluded or afflicted with stenosis (Fig. 1). Therefore we aimed at biocompatible DLC films coated on a coronary stent which has both biocompatibility and durability required for a implantable medical device. Fig. 2 shows a photograph of a coronary stent. From the viewpoint of plasma surface treatment technology, the deposition process of DLC films provides sufficient adhesion and biocompatibility to resolve the problems of implantable medical devices.

2. High-Tenacity DLC Thin Films for Stents

A coronary stent is placed and expanded by a balloon catheter to the plastic deformation region to open an occluded coronary artery, thus the biocompatible coating on the stent must follow the changing surface of the stent without showing any cracking. Therefore, we have examined the formation of high-tenacity concentration gradient type DLC films that were made to imitate the plastic deformation of the based stent material by adjusting the amount and concentration gradient of the Si doped into the DLC films. As a result, we have created new DLC nano-coating thin films with Si concentration increasing during the doping in DLC deposition process. These new DLC films have the superior adhesion feature which does minimize cracking on the surface of coronary stent during expansion. These new DLC films have been deployed on a new domestic coronary stent which is approved the European CE marking in 2008 and now under clinical evaluation in Europe.

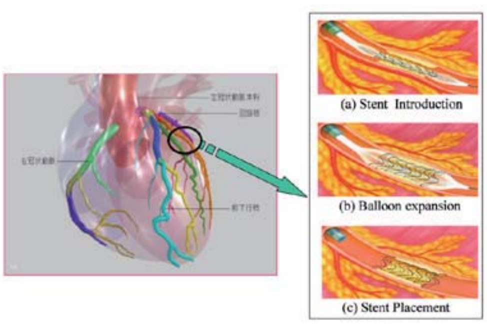

Fig. 1 Schematic illustration of the coronary interventional angioplasty1,2).

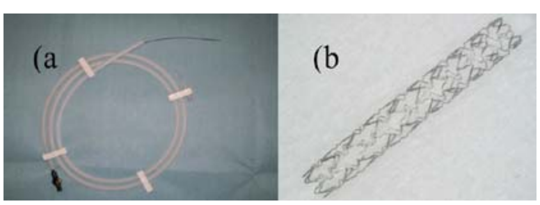

Fig. 2 Photograph of the coronary stent. (a) Stent delivery system, (b) Expanded stent(Φ3.5mm).

3. Applications of DLC Thin Films to Coronary Drug-Eluting Stent

A drug-eluting stent is to release slowly and continuously its coated drug on the surface to the inside of coronary artery. To avoid injury or inflammation, the DLC-coated surface should not be cracked. Using plasma surface treatment techniques on these high-tenacity DLC films, we can improve the adhesive property of the biodegradable polymer layer contained with antithrombotic drug which inhibits any allergic action after the complete releasing the drug into the blood vessel (Fig. 3). Animal studies and hemopathological analyses have been performed

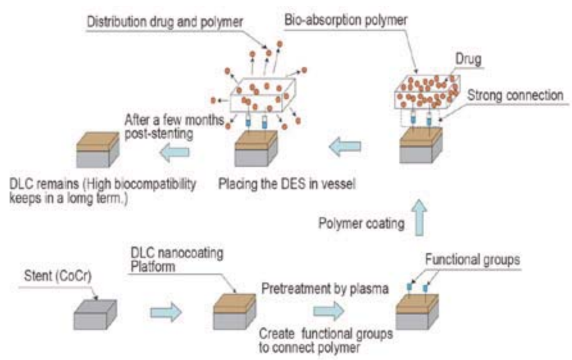

Fig. 3 Schematic illustration of the plasma surface engineering for coating of drug-eluting stent.

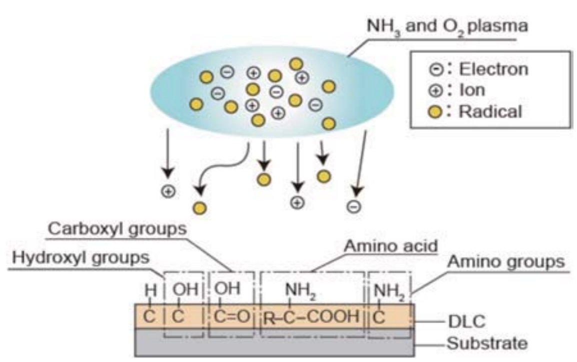

Fig. 4 Schematic of the DLC films surface with introduced functional groups using plasma.

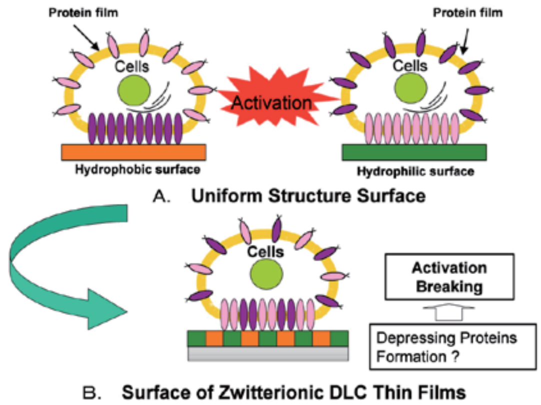

Fig. 5 Image of the mechanisms behind the high compatibilities on DLC films with controlled zeta potential for medical material application.

on mini-pigs to confirm the safety and efficacy in the USA. As a result, the strut-associated inflammation was minimal with occasional macrophages were reported. Endothelialization was nearly complete with mild sub endothelial inflammation seen in each segment. And, fibrin deposition was minimal. This biocompatible drug-eluting stent with the new DLC films is expected to be realized in near future.

4. DLC Thin Films with Controlled Zeta Potential of Biomaterials

Histocompatibility with human coronary artery endothelial cells or smooth muscle cells requires the implanted stent surface with properties other than blood compatibility to come into contact with vascular tissue. Concurrently we have been developing multifunctional stents of next generation. We are focusing particularly on the interaction between the DLC surface and the biomaterial surface. We have investigated new biomimetic DLC films with the zeta potential of their surfaces controlled by plasma modification techniques for the purpose of improving cytocompatibility with the tissue cells, which are generally negatively charged. As a result, we found that controlling the zeta potential was enabled with introduction of both anionic and cationic functional groups into the DLC films surface (Fig. 4). Additionally, blood compatibility and tissue cell compatibility of the new biomimetic DLC films was confirmed, and it were suggested that the optimization of zeta potential on the zwitterionic structural surface could be realized with the new DLC films. We considered that the amount and type of functional groups, and the nano-distance between anionic and cationic functional groups affect the tissue cells compatibility (Fig. 5). The functionality of biomimetic DLC films on medical devices have been improved by plasma surface modification techniques and these DLC films will provide the opportunity to develop innovative and new advanced medical devices in the near future.

5. Conclusion

The application and experience of DLC thin films on a coronary artery stent is introduced to comply with the demands specifically for biocompatible medical devices as well as the plasma processing required for biocompatible DLC films in this paper. Furthermore, we are introducing the future prospects concerning the possibility of the biomimetic DLC films used for advanced medical devices which could be realized through precise control of plasma processing.

Acknowledgements

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References

1) National Cardiovascular Center H.P., http:// www.kanazawa-heart.or.jp/byoki/byoki.html
2) Kanazawa Cardiovascular Hospital H.P.,http:// www.ncvc.go.jp/cvdinfo/Sick/ sick41.html

Novel laser applications to 3-D micromachining and high-resolution measurement for micro/nano-manufacturing

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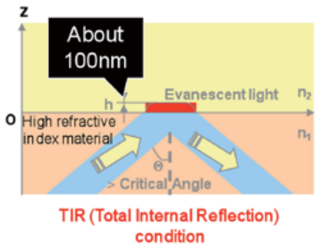
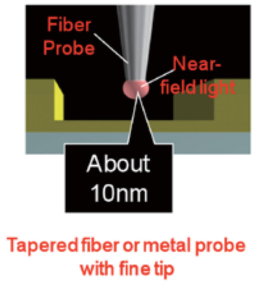
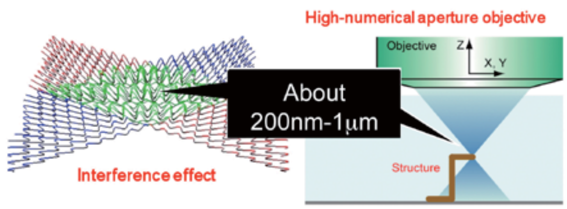
Continued from page 1 measurement techniques from the viewpoint of localized light energy on an engineering surface. Here, the localized light energy is mainly classified into three types according to its property, namely, the evanescent light energy, the near-field light energy, and the focused light and standing wave energy of propagating beam as shown in Table 1.

2. Evanescent light energy application to nano-stereolithography

Micro-stereolithography is a common rapid prototyping technology, allowing the fabrication of complex 3-D microstructures by curing liquid photosensitive resin. It has been shown that by a layer-by-layer process, 3-D devices with micrometer resolution can be rapidly fabricated, while a two-photon-absorption process has

Table 1. Localized light energy and its property

Evanescent light energy	Near-field light energy	Focused light and standing wave energy of propagating beam
•Size: about 100nm. •Localizing perpendicularly to the total internal reflection surface.	•Size: about 10nm. •Localizing at the tip of the near-field light probe.	•Size: about 200nm – 1μm. •Localizing with high flexibility and controllability. •Restricted by the diffraction limit.
		

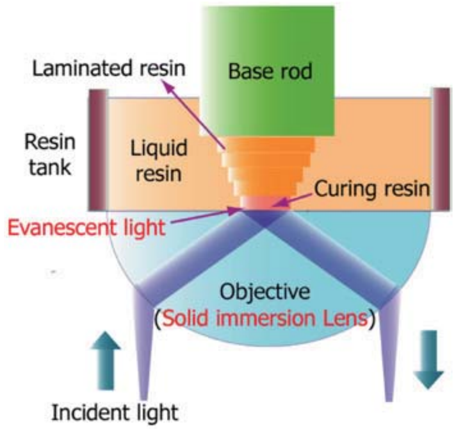


Fig. 1 Nano-stereolithography using evanescent light energy

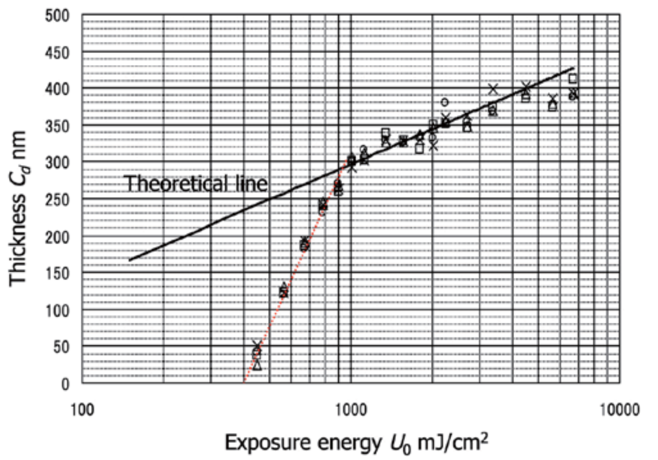


Fig. 2 Semilogarithmic graph of the cure depth with exposure energy (P-polarization, 220mW/cm2)

recently improved its spatial resolution. However, the former is not able to realize sub-micrometer resolution and the latter requires an expensive femtosecond laser.

We intend to establish a micro-stereolithography method which allows rapid sub-micrometer fabrication through improvement of the layer-by-layer process by paying attention to its potential of curing large areas at a single exposure. In the conventional layer-by-layer process, since the propagating light, used as the exposure energy, is transmitted through the photopolymer, the cure depth (polymer thickness) exceeds 10 μm, thus not allowing sub-micrometer vertical resolution. And, it is almost impossible to achieve sub-micrometer horizontal resolution because the cure depth is greater than the focal depth of the objective lens of an imaging system. To resolve these issues, we propose a nano-stereolithography method that uses evanescent light, instead of propagating light, as the exposure energy (Figure 1). Evanescent light is partially localized energy at the boundary within the near-field region under total internal reflection; thus, the cure depth would be less than 1 μm. Our experiments showed 10 nm thickness can be also achieved by controlling the light power and the total internal incident angle as shown in Figure 2. These results indicate that nano-stereolithography has the ability to fabricate 3-D sub-micrometer structures with a high degree of controllability through integration with the layer-by-layer process.

3. Near-field light energy application to inspection of nanoimprint lithography

We are applying this near-field light energy to measurement of the residual thin-film (about 100nm or less) thickness for nanoimprint lithography (Figure 3). In nanoimprint lithography, the area of the residual thin-film is horizontally limited less than 100nm. So, the conventional optical thin-film thickness measurement methods such as ellipsometer cannot be applied due to its low ability of horizontal spatial resolution. Target of this research is to measure the residual thin-film thickness with the resolution of several nm non-destructively.

4. Standing wave energy application to high-resolution imaging for semiconductor patterned wafer inspection

Generally speaking, the spatial resolution of optical imaging is restricted by the diffraction limit as long as using the propagating light. In order to apply the

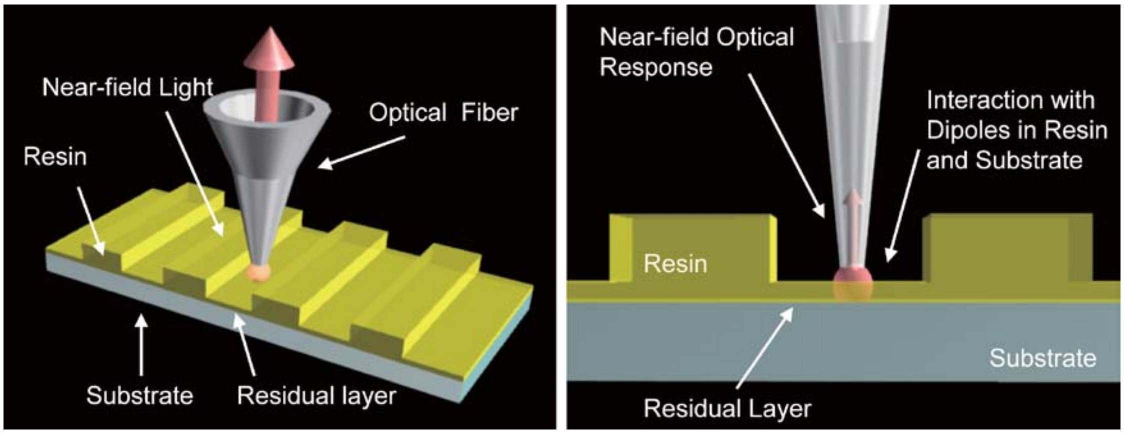


Fig. 3 Residual layer thickness measurement for nanoimprint lithography using near-field light energy

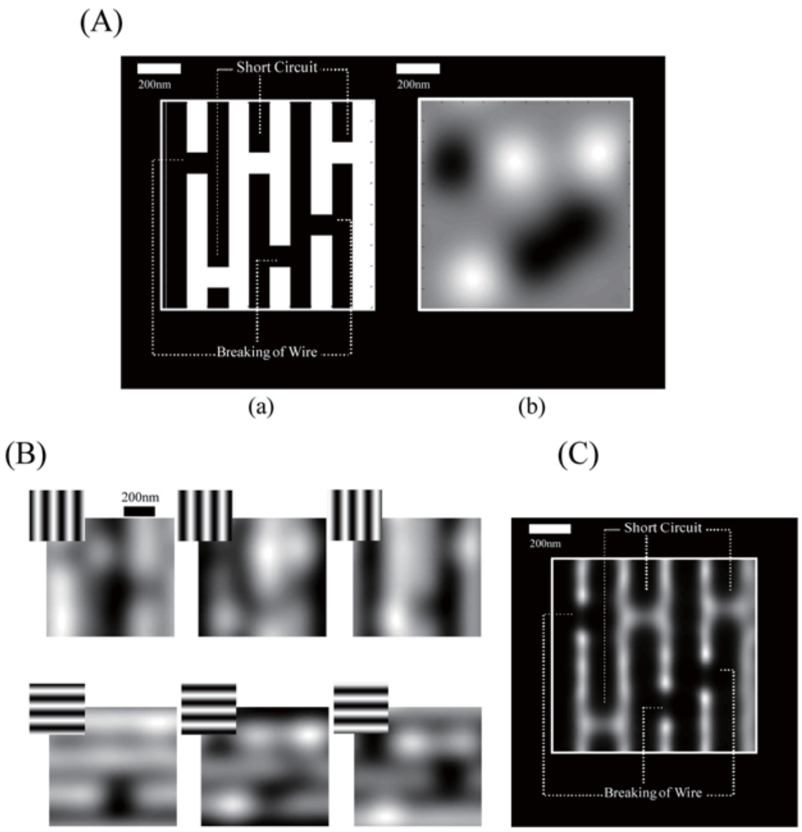


Fig. 4 High-resolution imaging beyond the diffraction limit using standing wave illumination shift
(A) Sample (a) and conventional optical image with normal illumination (b)
(B) Multiple optical images by standing wave illumination shift
(C) Reconstructed high-resolution image from the multiple optical images (B)

advantages of far-field optical imaging such as remote sensing to visual inspection of the engineering surface for the micro/nano manufacturing, high-resolution optical imaging beyond the diffraction limit is strongly needed. So, many super resolution methods are actively researched in these days. One of them is a combination of standing light wave illumination and image retrieval based on successive approximation. The localized energy size of standing wave distribution is not very small compared with the other localized light energies mentioned above. However this light energy based on the propagating beam does not need the approaching process of TIR surface, fiber probe tip, and so on. Then, we can easily perform the dynamic control of light energy distribution on the surface. In this method, instead of conventional uniform illumination, standing wave illumination is employed and multiple optical images are detected under shifting the lateral position of the standing wave distribution with nanometer scale. Since the corresponding illumination distributions for the multiple images are known, image retrieval with higher frequency is expected using those multiple modulated images with successive approximation. Figure 4 indicates a typical result of computer simulation for semiconductor patterns under the condition with wavelength of 488nm, N.A. of 0.95, and the Rayleigh diffraction limit of 313nm. The conventional optical image (Figure 4(A)(b)) with normal illumination means the semiconductor patterns with line and space of 100 nm cannot be resolved under this optical condition. Figure 4(B) shows the multiple optical images obtained shifting the standing wave illumination with the pitch of 300nm. Each modulated image is still restricted by the diffraction limit. And by performing the retrieval algorithm using these multiple diffraction-limited images, a reconstructed high-resolution image can be achieved as shown in Figure 4(C). The fundamental verification experiments showed that the actual semiconductor patterns with line and space of 200nm can be clearly resolved using the optics with the Rayleigh diffraction limit of 590nm (N.A. of 0.55).

5. Conclusions

The localized property of light is one of the most important factors, determining the fundamental characteristics of the machining and the measurement techniques using the light energy, because the controllable spatial resolution strongly depends on the localized size of light energy. So, especially in the micro/nano-manufacturing, it is important to consider the applications being designed to correspond with the localized properties of light energy. These works introduced above were partially supported by JSPS under the Grant-in-Aid for Scientific Research (B), NEDO under the Industrial Technology Research Grant Program, and TEPCO Research Foundation.

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