Revista Brasileira de Expressão Gráfica

CREATION OF 3D MODELS FROM *SEM IMAGES* OF FINE PROTRUSIONS FORMED BY *SPUTTER-ETCHING* OF STAINLESS STEEL

CRIAÇÃO DE MODELOS 3D A PARTIR DE *IMAGENS SEM* DE PROTRUSÕES FINAS FORMADAS PELA GRAVAÇÃO POR *SPUTTER-ETCHING* DE AÇO INOXIDÁVEL

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Abstract: Modification of gripping ability of instrument and machine parts is one of the most impotant demands, e.g., for tweezers and a friction roll handling and conveying soft bodys and sheets. Although various shapes of protrusions with bottom sizes ranging from 200 nm to 50 *μ*m can be formed on steels by argon ion sputter-etching and the gripping ability is measured by friction tests, preparation and execution of a large number of experiments is time- and cost-consuming. Thus, it is necesarry to develop a software to predict the gripping ability of protrusions. This paper presents an approach for creating 3D models of fine protrusions from their scanning electron microscope (SEM) images, which is an essential part of the analysis and simulation. A large-scale 3D model of protrusion was created efficiently by transfering the 3D data to a software programed using Hermite function, and the protrusions were well reproduced by the software. These models will be used in finite element method (FEM) and moving particle semi-implicit method (MPS) to calculate the deformation of soft bodies and the gripping forces without slipping. The results will be applied to the development of a software to find the optimum protrusion shapes and sizes depending on the properties and shapes of soft and slippery bodies.

Keywords: sputter-etching, fine protrusion, SEM image, coordinate recognition, 3D model.

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Resumo: A modificação da capacidade de preensão de peças de instrumentos e máquinas é uma das demandas mais importantes, por exemplo, para pinças e rolos de fricção usados no manuseio e transporte de corpos macios e folhas. Embora várias formas de saliências com tamanhos de fundo variando de 200 nm a 50 μm possam ser formadas em aços por corrosão catódica de íon argônio e a capacidade de preensão seja medida por testes de fricção, a preparação e execução de um grande número de experimentos consome tempo e gera custos. Portanto, é necessário desenvolver um software para prever a capacidade de preensão das saliências. Este artigo apresenta uma abordagem para a criação de modelos 3D de saliências finas a partir de suas imagens de microscópio eletrônico de varredura (MEV), parte essencial da análise e simulação. Um modelo 3D de protuberância em grande escala foi criado de forma eficiente, transferindo os dados 3D para um software programado usando a função Hermite, e as protuberâncias foram bem reproduzidas pelo software. Esses modelos serão usados no método dos elementos finitos (MEF) e no método semi-implícito de partículas em movimento (MPS) para calcular a deformação de corpos moles e as forças de preensão sem escorregamento. Os resultados serão aplicados ao desenvolvimento de um software para encontrar as formas e tamanhos de protuberância ideais, dependendo das propriedades e formas de corpos macios e escorregadios.

Palavras-chave: *sputter-etching*, protrusão fina, imagem *SEM*, reconhecimento de coordenadas, modelo 3D.

1 Introduction

Recently, many computer software incorporated with modeling, simulation and graphics are widely applied to solve various engineering problems. This will be also useful to express the mechanical and physical interactions between solid and solid, liquid and solid, and gas, ion or light and solid. In these cases, the surface textures of solid, such as protrusions, dots, and holes, are the most important factors to control the interaction. Fine protrusions have many functions such as superhydrophobicity and superhydrophilicity, high visible- and infrared-light absorptance, high friction or gripping ability, etc. Each function is strongly dependent on sizes, shapes and distribution of protrusions. For the surface to absorb visible light, the sizes and intervals of protrusions should be distributed within wave lengths ranging from 400-800nm. If limited to gripping ability, a friction roll to convey sheet materials, such as paper, cloth and soft polymer sheet, and a medical tweezers or forceps to grip a soft and slippery suture, blood vessel or tissue, need specially shaped protrusions. In these cases, if cone-shaped protrusions are applicable, the size, density and sharpness of protrusions should be selected depending on the hardness, surface roughness, and damage tolerance of gripped materials.

One of the most effective and economic method to fabricate the protrusions is to utilize the sputter-etching of matals and alloys using argon or xenon plasma (WEHNER, 1971, WITCOMB, 1974, AUCIELLO, 1984). Figure 1 shows examples of cone-shaped protrusions formed by argon iion sputter-etching of stainless steel (NAKASA, 2018). These fine protrusions have excellent mechanical properties and provide high gripping ability for soft polymer and fiber sheets (NAKASA, 2010, NAKASA, 2015, NAKASA, 2019, NAKAMURA, 2021).

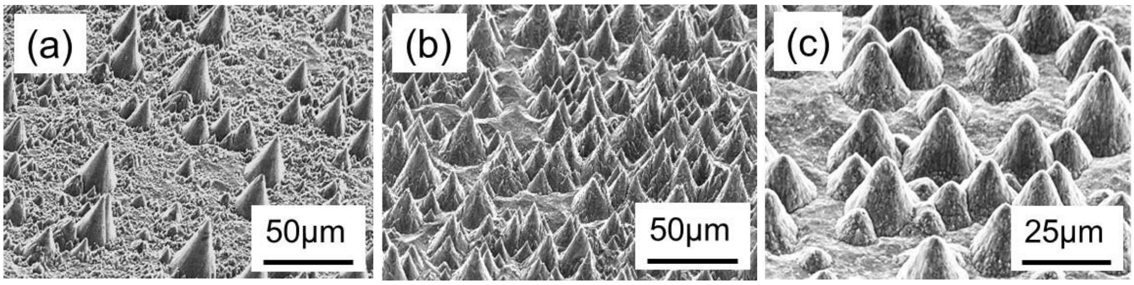


Figure 1 - Fine cone-shaped protrusions with various density and sharpness formed on AISI 420 stainless steel by sputter etching

However, because there are so many combinations between protrusion shapes and soft bodies with different shapes and surface properties, development of a software to select the optimum protrusion shapes, or “Gripping Software”, is necessary. Figure 2 illustrates the outline of our research project including fabrication of protrusions, gripping tests, recognition of 3D coordinates of protrusion vertexes, creation of 3D models and their graphic display, calculation of stresses and strains, construction of data base for the gripping software.

In order to calculate the stresses and strains through FEM or MPS (KOSHIZUKA, 2001, CHIKAZAWA, 2001), 3D models of fine protrusions are needed. However, it is time consuming to create a lot of different fine protrusions with general-purpose 3D-CG or CAD software. In the present research, we propose an approach for creating 3D models of fine protrusions, which is an essential part of the project: (1) Take scanning electron microscope (SEM) images of fine protrusions from different directions. (2) Forward the images into a CG software to calculate 3D coordinates of fine protrusion vertexes. (3) Forward the 3D coordinates into an original software developed by the authors to create the 3D models.

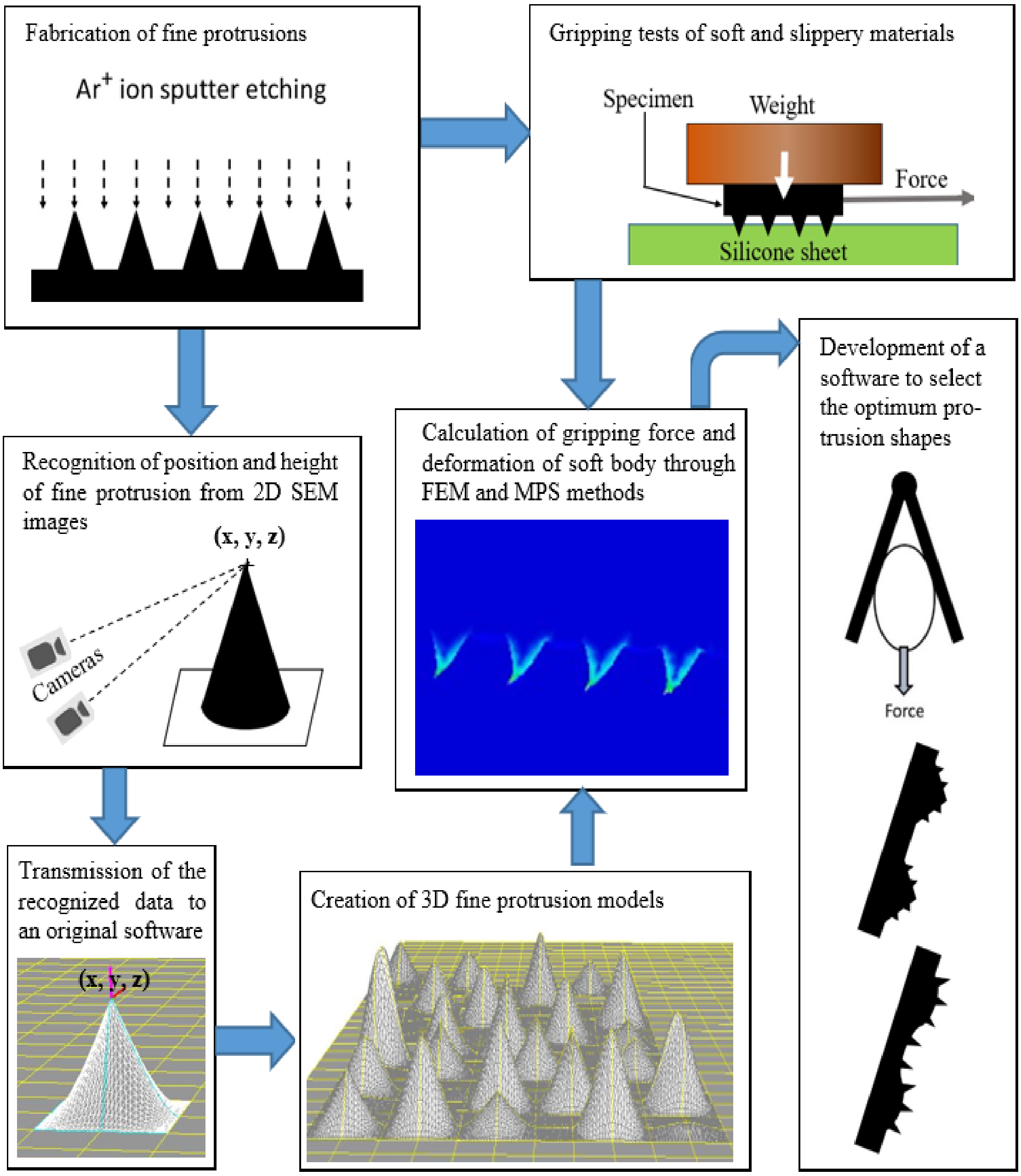


Figure 2 - Flow of present research to develop a software to select the optimum protrusion shapes for gripping soft and slippery bodies

2 Preparation of protrusion specimen and taking SEM images

Only the sputter etching of AISI type 420 (JIS: SUS420J2) martensitic stainless steel is introduced here (NAKASA, 2018). An as-received steel square bar (20mm×20mm section) was cut to a specimens of 5 mm thickness, and the surface was polished with emery papers up to #1600 and ultrasonically cleaned in ethyl-alcohol. The specimens were placed on a type 304 stainless steel disk with 100 mm diameter set on the copper cathode electrode of a radio-frequency magnetron sputtering apparatus (Sanvac Co.: SP300-M). After vacuum pressure fell below 6×10^{-3} Pa, argon gas was introduced and maintained at a pressure of 0.67Pa. The sputter-etching of the specimens was carried out at a sputter power of 250 W for 7.2ks.

Figure 3 shows an example of gripping tests of polymer sheets using the protrusion specimen shown in Figure 1(a) and the apparatus shown in Figure 2. Friction coefficient exceeds one, which means that the protrusions have a large gripping ability.

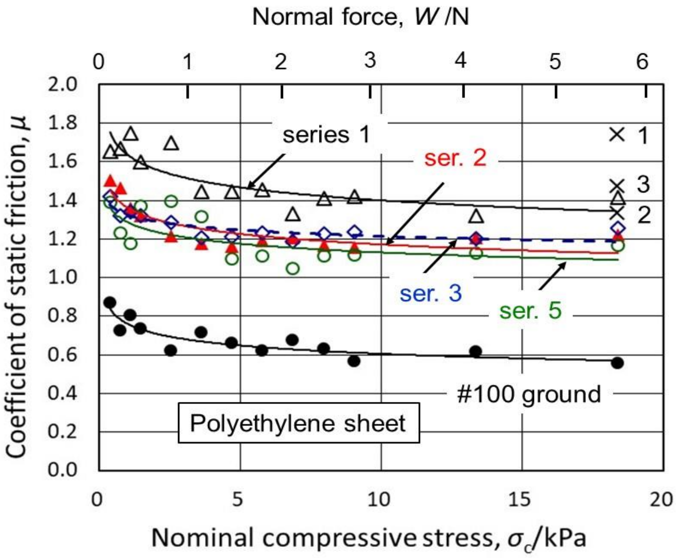


Figure 3 - Relationships between nominal compressive stress and friction coeficient

The distribution of protrusions was observed using a SEM (S-4700, Hitachi Co.).

The specimen was fixed on a 45° angle block which was set on the table of the SEM as shown in Figure 4. Fine cone-shaped protrusions on the specimen surface as is shown in Figure 5 was photographed at different rotation angles of the table. The average vertex angle of protrusions was 40°, and this value was applied to all the protrusions in the following modeling process.

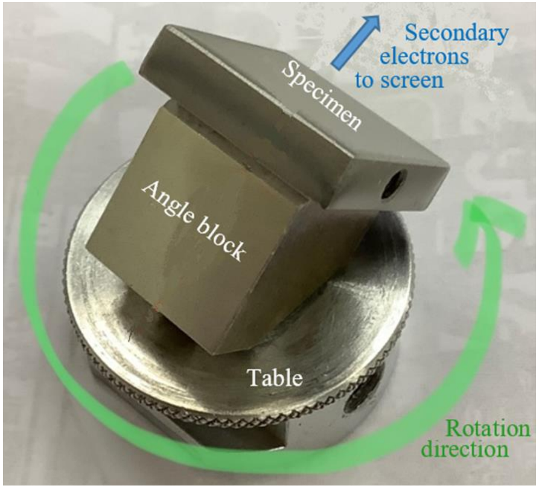


Figure 4 - Installation of the specimen in SEM

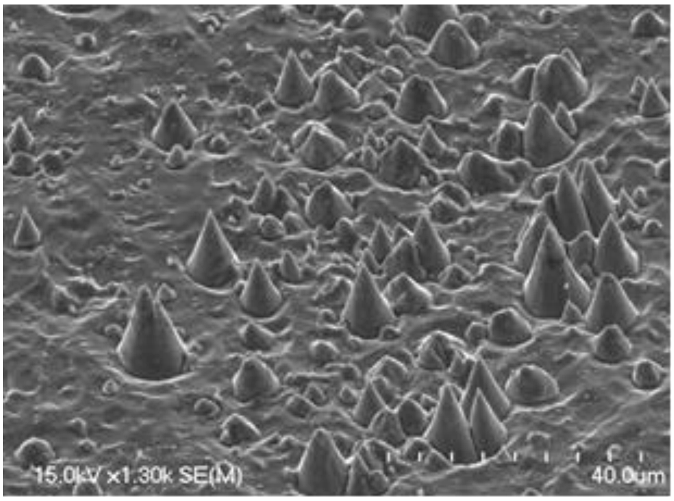


Figure 5 - A SEM image of protrusions (tilting angle: 45°, acceleration voltage:15 kV)

3 Calculation of 3D coordinates of feature points from images

A fundamental issue here is how human beings and animals view various shapes and size of objects and establish their 3D images. The key is the stereo viewing function of their eyes. A similar function can be achieved with two cameras taking more than two 2D images of an object. It is based on triangulation, a technique in which distances and directions are estimated from an measured baseline and the principles of trigonometry.

Figure 6 shows the principle of constructing a 3D object from its 2D images. The distance between two cameras e_1 and e_2 is *d*, the origin of coordinate system (x, y, z) is located at the middle point of line segment e_1e_2, point s is on the line e_1e_2, and line ps is perpendicular to the line e_1e_2. The coordinates of arbitrary 3D point $p(x_p, y_p, z_p)$ can be calculated from angles of observation α_1, α_2 and θ according to the following equations.

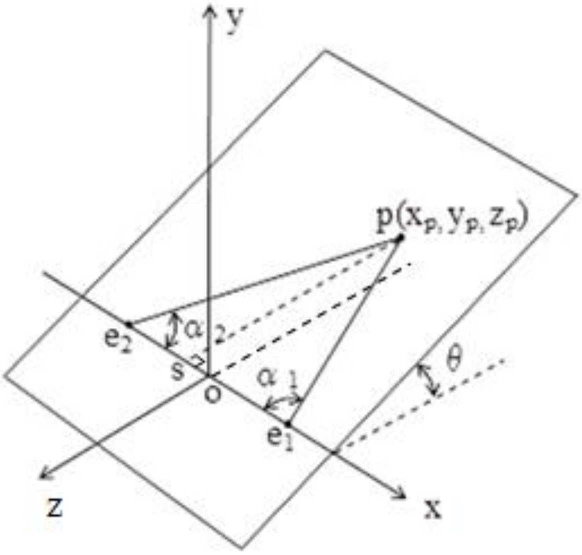


Figure 6 - Principle of constructing a 3D object from 2D images

Since

$$d = \overline{e_1e_2} = \overline{e_1s} + \overline{se_2} = \overline{ps}/\tan\alpha_1 + \overline{ps}/\tan\alpha_2 \tag{1}$$

so that

$$\overline{ps} = \frac{d\tan\alpha_1\tan\alpha_2}{\tan\alpha_1 + \tan\alpha_2} \tag{2}$$

because

$$\overline{os} = \overline{e_1s} - \overline{e_1o} = \overline{e_1s} - d/2 \tag{3}$$

$$\overline{os} = \overline{oe_2} - \overline{se_2} = d/2 - \overline{se_2} \tag{4}$$

From Equations (3) and (4), we have

$$\overline{os} = (\overline{e_1s} - \overline{se_2})/2 \tag{5}$$

Then the coordinates x_p, y_p, z_p are obtained as follows:

$$\begin{aligned} x_p &= -\overline{os} \\ &= -(\overline{e_1s} - \overline{se_2})/2 \\ &= -(\overline{ps}/\tan\alpha_1 - \overline{ps}/\tan\alpha_2)/2 \\ &= \frac{d(\tan\alpha_1 - \tan\alpha_2)}{2(\tan\alpha_1 + \tan\alpha_2)} \end{aligned} \tag{6}$$

$$\begin{aligned} y_p &= \overline{ps}\sin\theta \\ &= \frac{d\tan\alpha_1\tan\alpha_2\sin\theta}{\tan\alpha_1 + \tan\alpha_2} \end{aligned} \tag{7}$$

$$\begin{aligned} z_p &= \overline{ps}\cos\theta \\ &= \frac{d\tan\alpha_1\tan\alpha_2\cos\theta}{\tan\alpha_1 + \tan\alpha_2} \end{aligned} \tag{8}$$

Note that the cameras are different from human eyes, and both the photo taking directions and focal distances vary. The locations of cameras should be determined from images of the object before calculation of coordinates of points on the object.

A CG software (3DM-Modeler, 3D MEDiA) based on the above principle was used in this research. In general, for constructing a 3D object, two or more images are needed, and interval of two photographing angles is between 5° and 15°. In the case of fine protrusions, the preliminary examination showed that two images were enough, and the best interval of two photographing angles was 5°. Two SEM images taken at 5° different rotation angles as shown in Figure 7 were input into the software. One was specified as a base image, another was linked to the base image to obtain the heights of the protrusions. Almost all correspondence points of the two images were extracted as shown in Figure 8. If a feature point (vertex of a fine protrusion) was not extracted (e.g. point P), it was added to the two images by mouse. Line segments for example AB can also be inserted to the two images for increasing the calculation precision. The calculated results were output in CSV format of Excel including coordinates of vertexes of the fine protrusions.

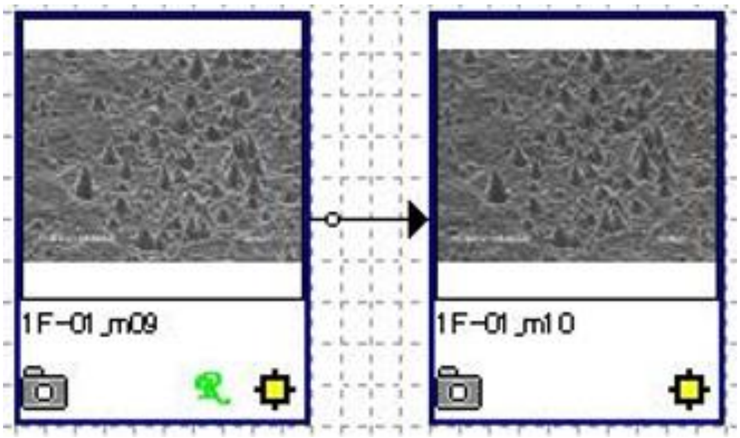


Figure 7 - A couple of the images with 5° different rotation angle

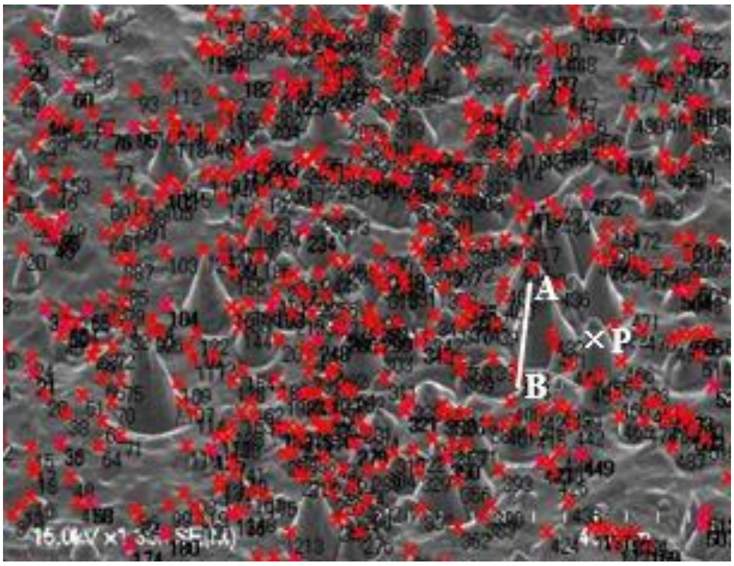


Figure 8 - Output of the 3D feature points

4 Creation of 3D models of the fine protrusions

The authors have developed a software for modeling fine protrusions (GAO, 2020), in a form of Hermite bicubic surface patch (S_{ij} at *i*-th row and *j*-th column) derived from horizontal squares, which are mathematically described by the Hermite equation (9) of two parameters *u*, *v* ($0 \leqq u \leqq 1$, $0 \leqq v \leqq 1$) (HUGHES, 2012, WATT, 2000). As shown in Figure 9 (JAMES, 2001), a curved surface patch is defined by sixteen boundary conditions including the four corner position vertexes (Q_{ij}, $Q_{i(j+1)}$, $Q_{(i+1)j}$, $Q_{(i+1)(j+1)}$), the eight tangent vectors ($\dot{Q}^{v}_{ij}$, $\dot{Q}^{v}_{i(j+1)}$, $\dot{Q}^{v}_{(i+1)j}$, $\dot{Q}^{v}_{(i+1)(j+1)}$, $\dot{Q}^{u}_{ij}$, $\dot{Q}^{u}_{i(j+1)}$, $\dot{Q}^{u}_{(i+1)j}$, $\dot{Q}^{u}_{(i+1)(j+1)}$) at the corner points (two at each point in the *u* and *v* directions) and the four twist vectors ($\ddot{Q}^{uv}_{ij}$, $\ddot{Q}^{uv}_{i(j+1)}$, $\ddot{Q}^{uv}_{(i+1)j}$, $\ddot{Q}^{uv}_{(i+1)(j+1)}$) at the corner points. The tangent vector at a corner point can be approximated by the direction and the length of chord lines joining the neighboring corner points. Hence, there is no need to input initial tangent vectors information and the computations required to calculate the surface parameters are simplified. The software is developed with Visual C++ and OpenGL.

$$
S_{ij}(u,v) = [u^3\ u^2\ u\ 1] \bullet \begin{bmatrix} 2 & -2 & 1 & 1 \\ -3 & 3 & -2 & -1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \bullet
\begin{bmatrix} Q_{ij} & Q_{i(j+1)} & \dot{Q}^{v}_{ij} & \dot{Q}^{v}_{i(j+1)} \\ Q_{(i+1)j} & Q_{(i+1)(j+1)} & \dot{Q}^{v}_{(i+1)j} & \dot{Q}^{v}_{(i+1)(j+1)} \\ \dot{Q}^{u}_{ij} & \dot{Q}^{u}_{i(j+1)} & \ddot{Q}^{uv}_{ij} & \ddot{Q}^{uv}_{i(j+1)} \\ \dot{Q}^{u}_{(i+1)j} & \dot{Q}^{u}_{(i+1)(j+1)} & \ddot{Q}^{uv}_{(i+1)j} & \ddot{Q}^{uv}_{(i+1)(j+1)} \end{bmatrix} \bullet
\begin{bmatrix} 2 & -3 & 0 & 1 \\ -2 & 3 & 0 & 0 \\ 1 & -2 & 1 & 0 \\ 1 & -1 & 0 & 0 \end{bmatrix} \bullet [v^3\ v^2\ v\ 1] \qquad (9)
$$

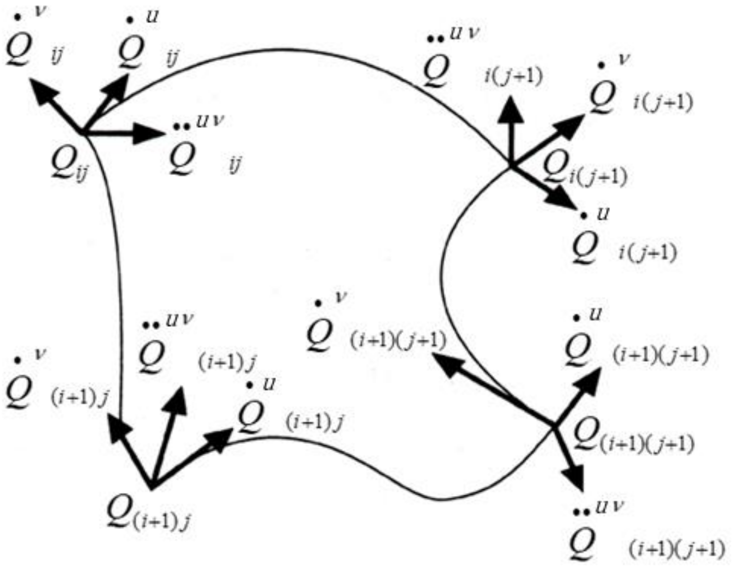
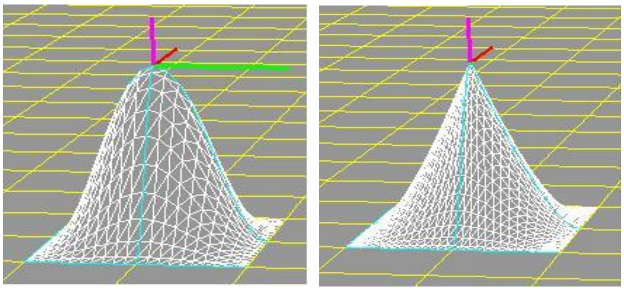
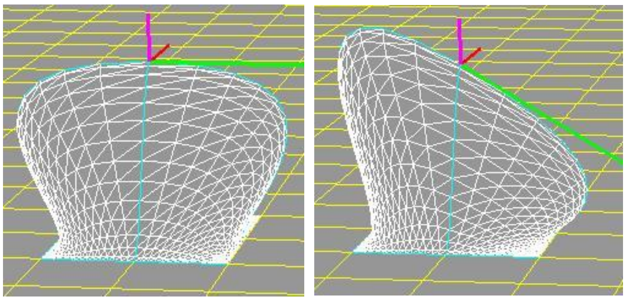


Figure 9 - Parameters of a Hermite bicubic surface patch

The software was implemented as shown in Figure 10 in the following steps. First, horizontal squares are defined. Next, each vertex is raised (Figure 10(a)) to a height to create four patches around it through computing their coordinates according to equation (9) to make up a protrusion, and the tangent vector is shortened (Figure 10(b)) or extended (Figure 10(c)) or rotated (Figure 10(d)) to change the shapes of the patches with position continuity and tangent continuity. A cone-shaped protrusion can be created by shortening the tangent vector as shown in Figure 10(b).



(a) Raising a vertex (b) Shortening a vector



(c) Extending a vector (d) Rotating a vector

Figure 10 - Variations of patches through changing the height and tangent at a vertex

In this research, in order to create 3D models of the fine protrusions automatically, the following programs were added to the software: (1) Extract coordinates of 3D feature points from the Excel CSV file. (2) Adjust the direction and scale of fine protrusions. Figure 11 shows an example of the created 3D model of protrusions. Almost of all the large cone-shaped protrusions were created. Although small protrusions were not represented well, they will not contribute to gripping and can be disregarded. The maximum number of modeled fine protrusions is about 10^6, which is enough for the FEM or MPS analysis and simulation. The creation of a protrusion is very fast by using the proposed method. The 3D models of fine protrusions will be useful to develop a gripping software to find the optimum protrusion shapes and sizes depending on the properties and shapes of soft and slippery bodies.

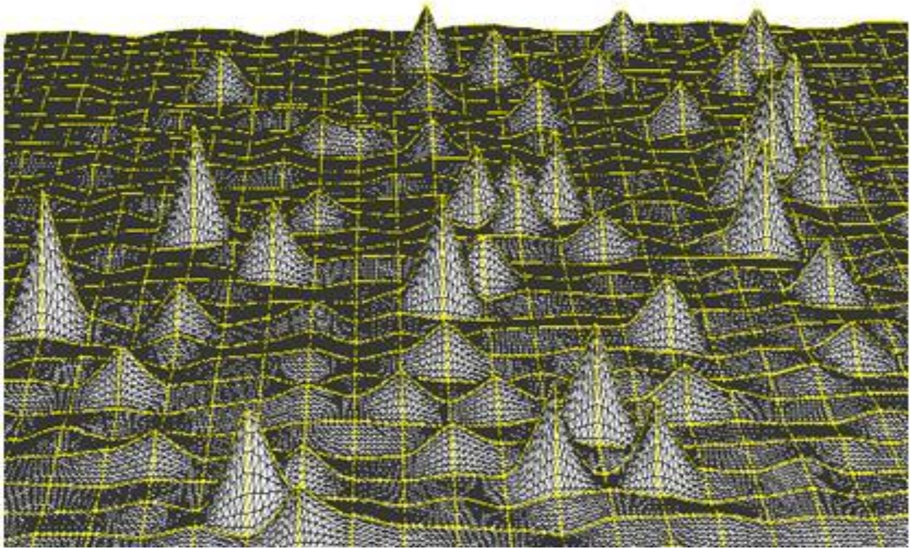


Figure 11 - The created 3D model of protrusions

5 Conclusions

A CG software 3DM-Modeler developed in the present research can recognize the 3D coordinates of vertexes of fine protrusions from their SEM images. In that case, two images are enough, and the best interval of two photographing angles is 5°. Inserting line segments to the 2D images can increase the recognition precision. The software can create 3D models of fine protrusions effectively and exactly. The 3D models will be used in FEM or MPS analysis to calculate stresses and strains at different gripping forces. The results will be applied to the development of a gripping software to find the optimum protrusion shapes and sizes depending on the properties and shapes of soft and slippery bodies.

Acknowledgments

This work was supported by JSPS KAKENHI Grant Number 20K04246.

References

WEHNER G. K. and Hajicek D. J.. Cone formation on metal targets during sputtering. **Journal of Applied Physics**, 1971.42(3): 1145–1149.

WITCOMB M. J.. The development of ion-bombardment surface structures on stainless steel. **Journal of Materials Science,** 1974.9: 551–563.

AUCIELLO O. and Kelly R.. **Ion bombardment modification of surfaces**. Amsterdam, Elsevier, The Netherlands, 1984.

NAKASA K., Yamamoto A. and Sumomogi T.. Gripping and frictional-convaying characteristics of fine protrusions formed by sputter-etching of stainless steels. **Transactions of the JSME**, 2018.84:https//doi.org/10.1299/transjsme.17-00360.

NAKASA K., Yan X., Yoshida M. and Sumomogi T.. Deformation characteristics of fine protrusions formed by sputter-etching of stainless steels. **Journal of solid Mechanics and Materials Engineering**, 2010.7(4): 1103-1110.

NAKASA K., Yamamoto A., Wang R. and Sumomogi T.. Effect of plasma nitriding on the strength of fine protrusions formed by sputter-etching of AISI type 420 stainless steel. **Surface & Coating Technology**, 2015.272:298 -308.

NAKASA K., Gao S., Yamamoto A. and Sumomogi T.. Plasma nitriding of cone-shaped protrusions formed by sputter etching of AISI 420 stainless steel and their application to impression punch to form micro-holes on polymer sheets**. Surface & Coating Technology**, 2019.358:891-899.

NAKAMURA M., Nakasa K., Kitamika Y., Gao S. and Sumomogi T.. Formation of fine protrusions by sputter etching of stainless steels and evaluation of gripping ability of fiber sheets. **International Journal of Precision Engineering and Manufacturing**, 2021.22:689-696.

KOSHIZUKA S., Chikazawa Y. and Oka Y.. Particle method for fluid and solid dynamics. **Computational Fluid and Solid Mechanics**, 2001.2:1269-1271.

CHIKAZAWA Y., Koshizuka S. and Oka Y.. A particle method for elastic and visco-plastic structures and fluid-structure interactions. **Computational Mechanics**, 2001.27: 97-106.

GAO S.. Nakasa K. and Huang L.. Software development for modeling irregular fine protrusions formed by sputter etching. **Visual Computing for Industry, Biomedicine, and Art**, 2020.3(11):1-8.

HUGHES JF, van Dam A, McGuire M, Sklar DF, Foley JD, Feiner SK et al. **Computer graphics: principles and practice**, 3rd edn. Addison -Wesley Publishing Company, New Jersey, 2012.

WATT A.. **3D computer graphics**, 3rd edn. Addison-Wesley Publishing Company, New York, 2000.

JAMES D. F., Andries V. D., Steven K. F. and John F.. **Computer graphics: principles and practice**, 2nd edition in C. Addison-Wesley Publishing Company, 2001.