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Influences of whole-body vibration on roughness sensation

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ABSTRACT

"Texture" is one of the elements that contribute to the appearance of industrial products. It is an important element in improving a surface's added value. In this study, we quantified the surface of various irregular shapes using areal surface texture parameters compliant with ISO25178-2:2012. Then, we investigated the relations of roughness sensations and areal surface texture parameters. Moreover, we investigated the effects on a car passenger's sense of roughness when exposed to whole-body vibration. By investigating the areal surface texture parameters of textured surfaces, parameters that were effective for characterizing irregularities in different surfaces were described. In conclusion, design guidelines for surfaces that include tactile factors were suggested.

Keywords: 3D surface texture, Tactile, Design I-INCE Classification of Subjects Number(s): 72.9

1. INTRODUCTION

The texture is one of the important element for designing the appearance of technology products to make the value added surface of products by diminishing uneven color and luster and by adding contact sensation such as softness and roughness (1-3). The embossed products used for the inertia material of automobile are usually designed with not only the appearance but also with the tactile of humans (4, 5). However the physical reference of a surface which effects on tactile has been seldom reported (6, 7). Moreover the evaluation of tactile under the dynamic vibration environment is necessary because the products are supposed to be vibrated when a human is on automobile.

In this present report, the roughness was focused as the reference of tactile and the design reference considered roughness tactile was intended. The roughness sensation was quantified by roughness stimulation of the automobile inertia emboss product and the relationship between the roughness sensation and the surface texture as the physical reference was investigated. The surface texture parameter based on ISO25178-2 which was set in 2012 (8) was adapted for the evaluation. The surface texture parameter which was correlated to the roughness tactile was characterized and the roughness tactile difference between the static and vibrated dynamic situation was investigated. The boundary value of physical reference for roughness tactile was obtained and the design references for the texture include the roughness tactile was proposed.

2. METHODS

2.1 Stimulus

The emboss sample for automobile interior was used as the roughness stimulus. It was a plate of ABS resin and the dimensions of the plate were 10*58*2mm. The emboss pattern was two types as shown in Fig.1 and the depth of the emboss was 3 types and total six types (Stimulus A to F) were prepared.

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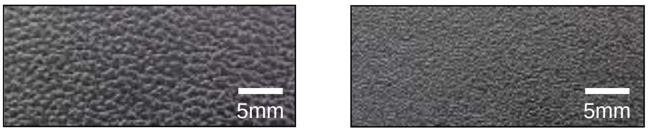


(a) Pattern I (Stimulus C) (b) Pattern II (Stimulus F)

Figure 1 – Typical photos of roughness stimuli.

2.2 Areal Surface Texture Parameters

High accurate 3D profiler CCI HD (Tayler-Hobson) was used for measuring a surface texture which measuring area was 1.8mm×1.8mm and the measurement resolution in horizontal and vertical direction were 1.75µm and 0.01nm respectively.

Table 1 Areal surface roughness parameters calculated and analyzed in this study.

	A	B	C	D	E	F	Unit	Name of parameters
Height parameters								
Sq	6.05	11.1	18.2	4.78	9.99	14.9	µm	Root mean square height
Ssk	-0.22	-0.37	-0.72	0.47	0.10	-0.16		Skewness
Sku	1.98	1.84	2.45	2.48	2.05	2.02		Kurtosis
Sp	14.6	21.3	29.1	16.5	26.5	31.1	µm	Maximum peak height
Sv	17.1	28.0	48.0	13.6	25.4	36.8	µm	Maximum pit height
Sz	31.7	49.4	77.1	30.1	52.0	67.9	µm	Maximum height
Sa	5.24	9.81	15.3	3.97	8.46	12.7	µm	Arithmetical mean height
Spatial parameters								
Sal	0.23	0.24	0.24	0.17	0.15	0.16	mm	Autocorrelation length
Str	0.72	0.79	0.72	0.76	0.58	0.82		Texture aspect ratio
Hybrid parameters								
Sdq	0.62	0.64	0.66	0.67	0.73	0.70		Root mean square gradient
Sdr	17.4	18.9	19.9	20.5	23.8	22.3	%	Developed interfacial area ratio
Functional and related parameters								
Smr	0.0007	0.0012	0.0011	0.0007	0.0013	0.0010	%	Areal material ratio
Smc	7.60	12.7	19.7	7.04	13.8	19.7	µm	Inverse areal material ratio
Sk	7.05	12.3	17.7	6.81	19.6	34.1	µm	Core height
Spk	1.41	1.92	2.43	4.62	3.98	3.63	µm	Reduced peak height
Svk	4.32	7.70	17.0	1.87	2.85	5.54	µm	Reduced dale height
*Smr*1	5.47	4.18	4.61	22.6	13.8	2.53	%	Material ratio
*Smr*2	77.5	73.3	70.3	94.4	95.1	89.0	%	Material ratio
Vv	0.0077	0.0129	0.0199	0.0072	0.0140	0.0200	mm^3/mm^2	Void volume
Vvv	0.0005	0.0008	0.0024	0.0003	0.0007	0.0014	mm^3/mm^2	Dale void volume
Vvc	0.0072	0.0121	0.0175	0.0069	0.0133	0.0186	mm^3/mm^2	Core void
Vm	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	mm^3/mm^2	Material volume
Vmp	0.0001	0.0002	0.0002	0.0002	0.0003	0.0003	mm^3/mm^2	Peak material volume
Vmc	0.0066	0.0132	0.0198	0.0044	0.0103	0.0158	mm^3/mm^2	Core material volume
Sxp	11.9	23.4	44.5	6.61	16.7	28.2	µm	Peak extreme height
Miscellaneous parameters								
Std	40.9	31.2	13.1	52.8	52.6	62.2	°	Texture direction
Feature parameters								
Spd	1253	186	7	1356	172	20	$1/mm^2$	Density of peaks
Spc	1467	1929	2380	1405	1969	2266	1/mm	Arithmetic mean peak curvature
*S*10*z*	16.5	19.0	31.5	16.6	24.5	39.3	µm	Ten-point height
*S*5*p*	5.50	7.00	18.0	5.96	9.32	23.6	µm	Five-point peak height
*S*5*v*	11.0	12.0	13.5	10.7	15.2	15.7	µm	Five-point pit height
Sda	0.0115	0.0322	0.1607	0.0092	0.0329	0.0858	mm^2	Mean dale area
Sha	0.0821	0.8597	9.0933	0.0579	0.9727	2.8933	mm^2	Mean hill area
Sdv	0.48×10^{-7}	0.85×10^{-7}	6.92×10^{-7}	0.39×10^{-7}	0.79×10^{-7}	2.35×10^{-7}	mm^3	Mean dale volume
Shv	1.27×10^{-7}	4.07×10^{-6}	8.87×10^{-4}	1.11×10^{-7}	1.85×10^{-5}	1.73×10^{-4}	mm^3	Mean hill volume

Table 1 shows areal surface texture parameters calculated by discrete data of measured surface in reference to ISO25178-2:2012. Fig. 2 shows 3D images of the measured surface. Table 1 and Fig. 2 reveal that the emboss patterns are almost same and the depth of emboss is different to three types in each pattern.

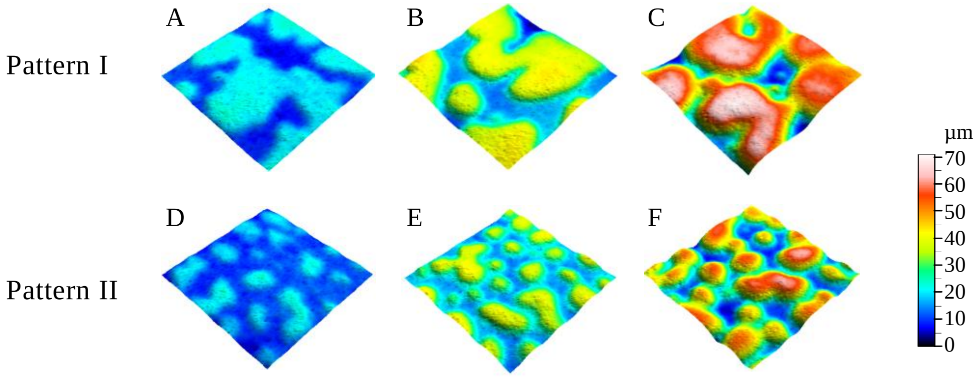


Figure 2 – 3D Images on roughness surfaces of stimuli.

2.3 Vibration condition

The dynamic vibrated environment was constructed by a driving simulator (hereinafter called DS) shown in Fig.3. The simulator body is mounted on a Stewart platform that has six prismatic joints driven by a DC motor. This allows the driving simulator to be moved in six degrees of freedom (6 DOF): three linear movements (x, y, and z) and three rotations (roll, pitch and yaw).

3 linear movements (x, y and z)
3 rotations (roll, pitch and yaw)

Figure 3 – Photo of the driving simulator.

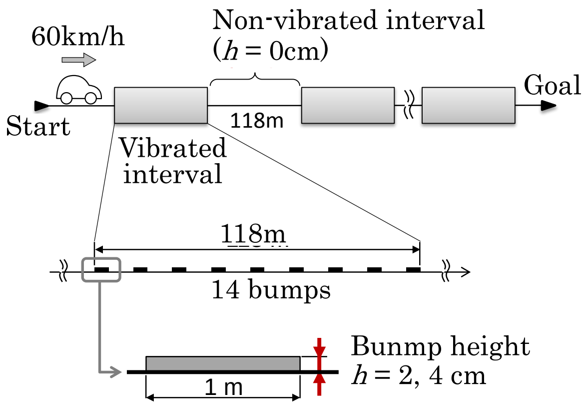


Figure 4 – A layout of the course.

The road was designed to arrange continues bumps in virtual space of DS and a participant received the vibration. Figure 4 shows a layout of the course. The straight course was designed to appear vibrated intervals and non-vibrated interval at random. The vibrated interval has 14 bumps which were 2 height conditions (h = 2, 4 cm). The non-vibrated interval had no height h=0cm bump. The participant was exposed to the vibration in 7 second by driving 60km/h on bump. The participant did not manipulate because of automatic operation.

Fig.5 shows acceleration effective value calculated from measured vibration on the seat under the 3 types of vibrated conditions based on ISO2631-1 frequency correction curve (9). These effective values are separated into “not uncomfortable” in case h = 0cm, “a little uncomfortable” in case h = 2 cm and “Uncomfortable” in case h = 4 cm compared to discomfort degree defined in ISO2631-1.

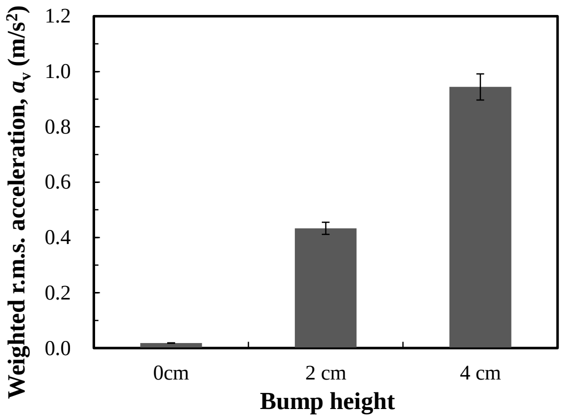


Figure 5 – The weighted r.m.s. accelerations during non-vibrated and vibrated intervals.

2.4 Participants

The participants were young healthy 10 men (22±0.7 years old) and 10 women (21±0.8 years old). Before starting each experiment, we obtained informed consent from all participants. In addition, this experiment was approved by The Bioethics Committee, which consisted of members from Kinki University, medical doctors, and common people.

2.5 Sensory assessment

2.5.1 Magnitude estimation method

The roughness sensation of the participant was calibrated by the magnitude estimation method (hereinafter called ME method) under non-vibrated circumstances to characterize the surface texture parameter which was correlated strongly to the tactile sensation. Firstly, the center roughness stimulus was provided to the participants. And 6 types of stimulus were provided 3 times at random in total 18 times. The participants replied verbally what stimulus number which was integer more than 1 accorded with the stimulus. The ratio of the roughness to previous one was calculated. The participants were requested to estimate the stimulus only by tactile, not by vision.

The geometric mean value for each stimulus was calculated by the roughness estimation from the participants. As the geometric mean value of stimulus F was as standard the geometric mean value of the other stimuli converted to ratio scale. The average of all participant stimulus value was defined as the roughness tactile ratio.

P and S are expressed by Stevens power function (10, 11) equation (1) where P, S, k and n are roughness sensation, roughness physical value, constant value and power number respectively.

$$P = kS^n \tag{1}$$

Equation (2) was logarithmic conversion of equation (1) and the linear regression between roughness sensation and physical value was calculated with least square method by using equation (2) to evaluate decision coefficient R^2.

$$\mathrm{Log}P = n\mathrm{Log}S + \mathrm{Log}k \tag{2}$$

Physical roughness value was defined as area surface texture parameter. The relationship between the roughness estimation and the area surface texture parameter was investigated and the high decision coefficient R^2 of surface texture parameter was defined as the physical reference of roughness.

2.5.2 Category Judgment method

The roughness sensation under vibrated situation was calibrated by category judgment method (12). The area texture parameter which was revealed to be correlated highly to roughness sensation in previous section was adapted as the physical roughness reference. The roughness sensation reference was defined as Table 2. The participants were requested to estimate the stimulus only by tactile, not by vision.

The participant sits on seat on DS and he or she operated DS to run the set course. When DS was running on the each different vibrated course an experimenter passed the stimulus to a participant and the participant decided the roughness value shown in Table 2. The participant estimated 6 types of stimulus 3 times at random in total 54 times. Same experiment was conducted under the static condition for comparison.

Table 2 – Relationship between category number and participant's response.

Category number	Participant's response
1	not rough
2	slightly rough
3	rough
4	very rough
5	extremely rough

3. RESULTS AND DISSCUSSION

3.1 Relation between areal surface texture parameters and roughness sensation

The relationship between the roughness sensation and the areal surface texture parameter was obtained by ME method. Table 3 shows the surface texture parameter higher than 0.9 of the decision coefficient, R^2. The decision coefficient of core material volume *Vmc* shows the highest number. Peak extreme height, *Sxp*, showed the second highest value of the decision coefficient R^2. Arithmetical mean height, *Sa*, Root mean square height, *Sq*, Maximum pit height, *Sv*, and Dale void volume, *Vvv* showed R^2 in order of lower value of decision coefficient.

Table 3 – The surface texture parameter and linear regression coefficient ($R^2 \geqq 0.9$)

	Areal surface texture parameters		n	K=log$k$	R^2
1	*Vmc*	Core material volume	0.92	2.184	0.994
2	*Sxp*	Peak extreme height	0.768	-0.61	0.986
3	*Sa*	Arithmetical mean height	0.994	-0.56	0.974
4	*Sq*	Root mean square height	0.993	-0.62	0.961
5	*Sv*	Maximum pit height	1.087	-1.17	0.954
6	*Vvv*	Dale void volume	0.704	2.525	0.908

Figure 6 shows the area material ratio curve to explain volume parameter, *Vmc* and *Vvv* and peak extreme height, *Sxp*. Area material ratio curve shows the load areal material ratio at cutting height. *Vmc* is defined as the volume enclosed with cutting sections of 10% and 80% of area material ratio.

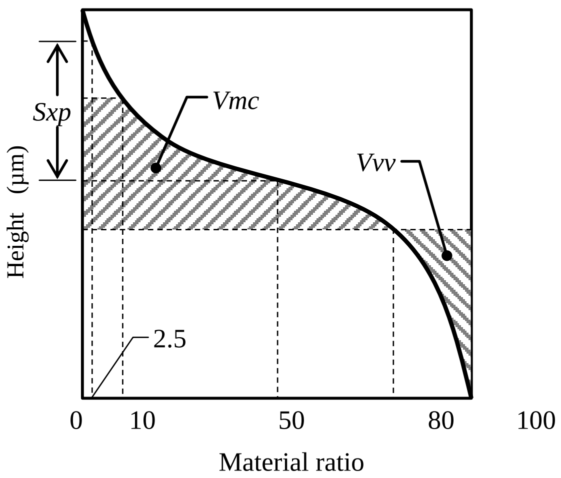


Figure 6 – Areal material ratio curve.

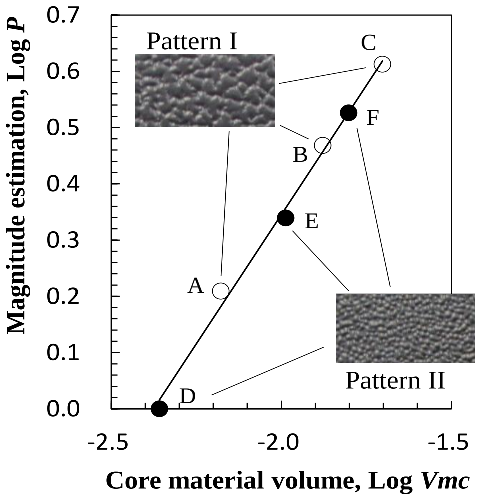


Figure 7 – Relationship between core material volume, *Vmc*, and scale of roughness sensation by using ME method.

Vmc is the material volume without huge convex and concave and shows the volume of macro convex. Peak extreme height, *Sxp*, is defined as the length between the cutting sections of 2.5% and 50% of area material ratio. *Sa* and *Sq* show arithmetic mean value and root-mean-square value in height direction, respectively. *Sv* is depth between the mean plane and the largest pit or valley. *Vvv* is dale void volume at material ratio 80%. The macro convex volume (*Vmc*) effected strongly on the roughness sensation. The roughness sensation seemed to be felt by the information of convex-concave amplitude such as the height at the peak (*Sxp*) , average height (*Sa*, *Sq*) and the depth of pit and valley (*Sv*, *Vvv*).

Figure 7 shows the relationship between core material volume *Vmc*, which showed the highest decision coefficient R^2, and roughness sensation value. As the depth of emboss is more *Vmc* is larger and the roughness sensation is large to be estimated rough. Therefore, it was considered that the macro convex and concave was estimated as roughness sensation by the participants. For the reference, the highest five of decision coefficient value did not differ between male and female.

3.2 Scales of roughness sensation

The frequency distribution table which indicated 5 step estimation of the roughness replied by 20 participants is shown Table 4. As shown in Figure 2 and Figure7, A to C and D to F in Pattern I and II indicated that the depth of emboss increased in stages and that *Vmc* increased as the depth of emboss altered deeper. The table replied both for Pattern I and Pattern II showed that the number of “Not rough” estimation increased as *Vmc* was smaller and the number of “Rough” estimation increased as *Vmc* was larger. The table replied under static condition showed that the number of “Not rough” estimation increased as *Vmc* was smaller and the number of “Rough” estimation increased as *Vmc* was larger. Moreover the number of “Not rough” estimation for same sample of Pattern I increased as the frequency increased. The relationship between the roughness sensation and the physical value was evaluated by the category judgment method (12).

Table 4 – The frequency distribution

(a) Non-vibrated condition

			Category 1	2	3	4	5
Pattern	I	A	35	21	3	1	0
		B	5	28	19	8	0
		C	2	6	26	17	9
	II	D	50	9	1	0	0
		E	11	31	13	5	0
		F	0	17	26	10	7

(b) Vibrated condition (h=0cm)

0cm			Category 1	2	3	4	5
Pattern	I	A	41	14	3	2	0
		B	0	28	19	11	2
		C	1	8	25	18	8
	II	D	51	8	1	0	0
		E	14	32	12	2	0
		F	0	17	26	8	9

(c) Vibrated condition (h=2cm)

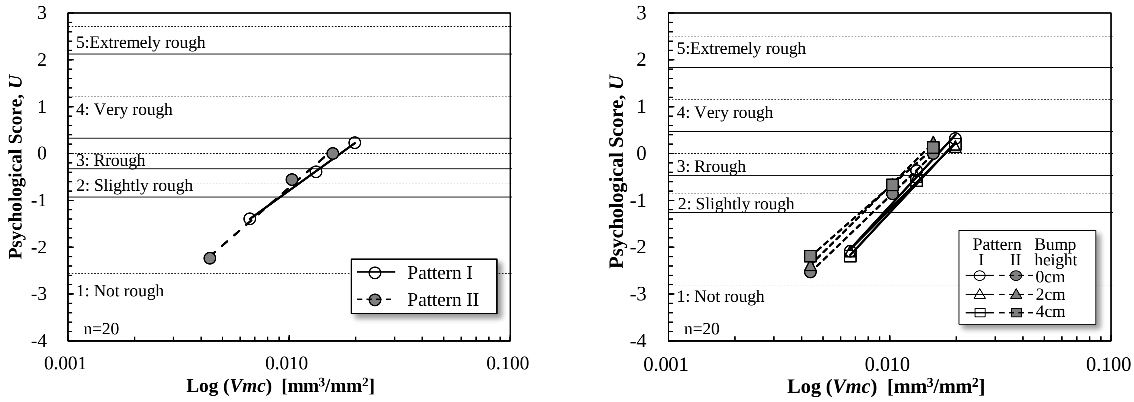
2cm			Category 1	2	3	4	5
Pattern	I	A	41	16	3	0	0
		B	5	26	18	11	0
		C	1	8	32	13	6
	II	D	47	12	1	0	0
		E	5	33	16	6	0
		F	0	11	25	17	7

(d) Vibrated condition (h=4cm)

4cm			Category 1	2	3	4	5
Pattern	I	A	43	14	3	0	0
		B	6	28	17	9	0
		C	0	8	31	16	5
	II	D	43	16	1	0	0
		E	7	31	18	4	0
		F	2	9	30	15	4

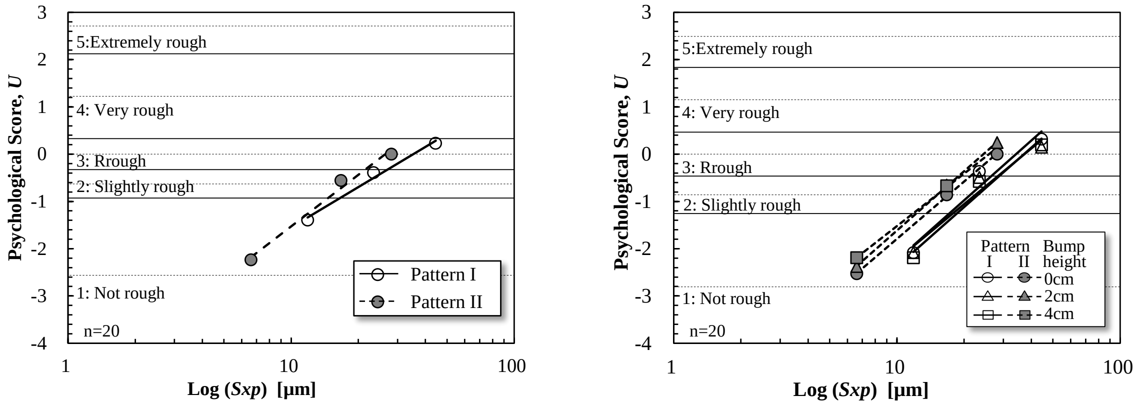
The relationship between roughness sensation and physical value is shown in Figure 8 to 13. The areal surface texture parameters in Figure 8 to 13 were used as the physical value of roughness. The result under static condition is shown (a) and the result under vibrated condition is shown in (b) for each figure. The dash horizontal line shows the center of each category and the solid line shows boundary of the category in the figure.

The figures confirm that the participants sense roughness as the values of areal surface texture parameters increases either the vibration exists or not exist. The result under static condition showed that the slope degree of regression line of Pattern I was higher than that of Pattern II. Therefore it was revealed that the roughness sensation changed to opposite direction when the areal surface texture differed. Moreover under the vibrated condition the value of each areal surface texture parameter of Pattern II resulted smaller than that of Pattern I when both of roughness sensations were same. Therefore it revealed that the embossed surface of Pattern II was evaluated rougher when the surface texture parameter was same. On the other hand, there seemed to be no deference of roughness sensations under between different vibrated conditions.



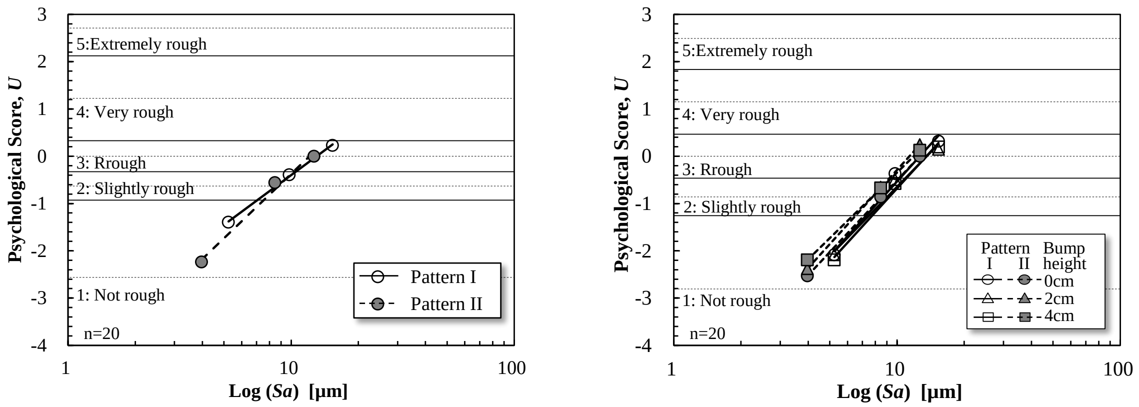
(a) Non-vibrated condition (b) Vibrated condition

Figure 8 – Relationship between core material volume, *Vmc*, and scale of roughness sensation by using category judgment method.



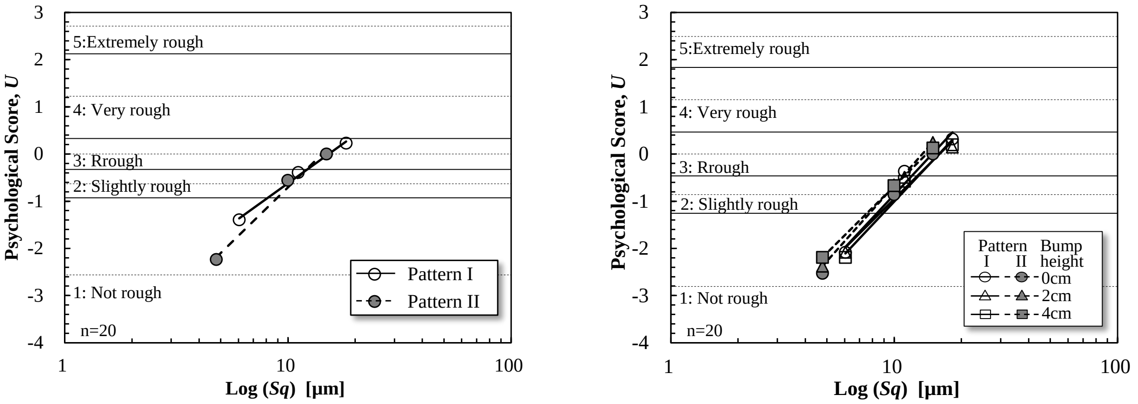
(a) Non-vibrated condition (b) Vibrated condition

Figure 9 – Relationship between peak extreme height, *Sxp*, and scale of roughness sensation by using category judgment method.



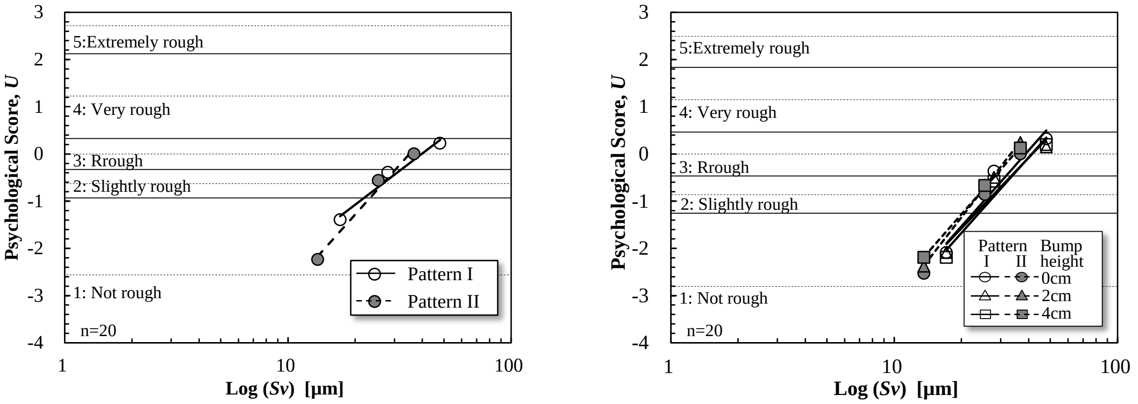
(a) Non-vibrated condition (b) Vibrated condition

Figure 10 – Relationship between arithmetical mean height, *Sa*, and scale of roughness sensation by using category judgment method.



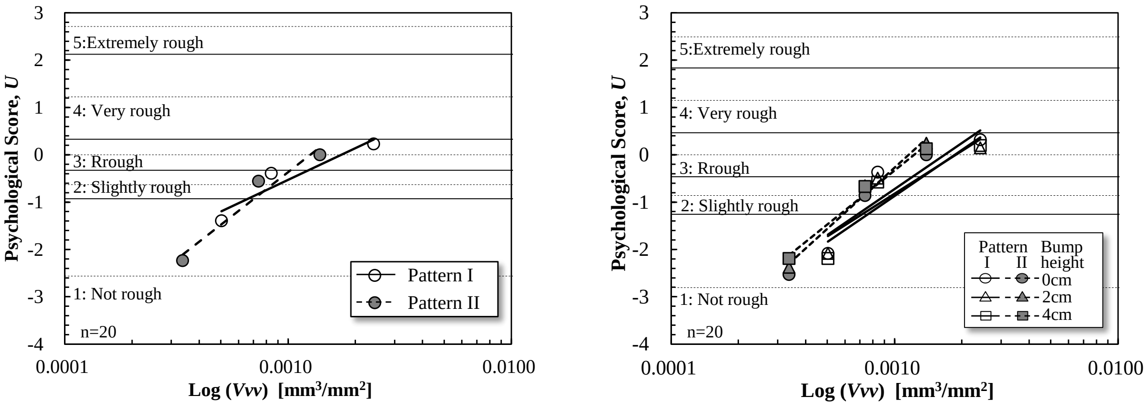
(a) Non-vibrated condition (b) Vibrated condition

Figure 11 – Relationship between root mean square height, *Sq* and scale of roughness sensation by using category judgment method.



(a) Non-vibrated condition (b) Vibrated condition

Figure 12 – Relationship between maximum pit height, *Sv*, and scale of roughness sensation by using category judgment method.



(a) Non-vibrated condition (b) Vibrated condition

Figure 13 – Relationship between dale vpod volume, *Vvv*, and scale of roughness sensation by using category judgment method.

The point where the regression line intersected the boundary line of each category was obtained and the roughness sensation threshold was shown in Figure 14 to 19. It was confirmed that the threshold interval and value of each pattern differed. As the result of physical value *Vmc* shown in Figure 14, when checking the result of bump height h = 2cm vibrated condition, Pattern II is sensed rougher than pattern I, which was considered that the finger tips became sensitive to the difference of macro convex volume. Therefore it was indicated that the value of *Vmc* needed to be about between 0.015 and 0.02 under vibrated condition to make the embossed surface which was estimated “rough” in case pattern I.

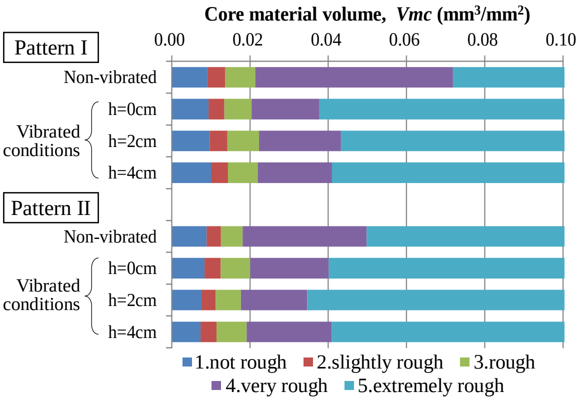


Figure 14 – Scales of roughness sensations. (Core material volume, *Vmc*)

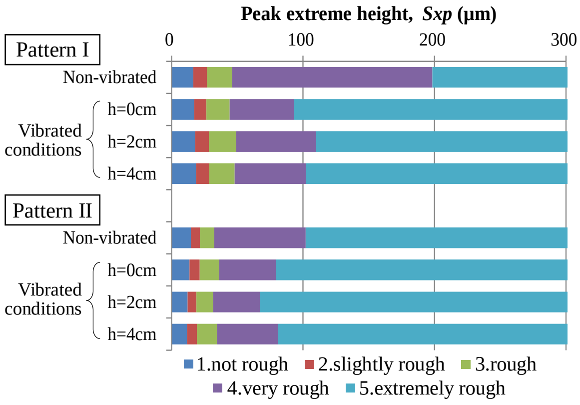


Figure 15 – Scales of roughness sensations. (Peak extreme height, *Sxp*)

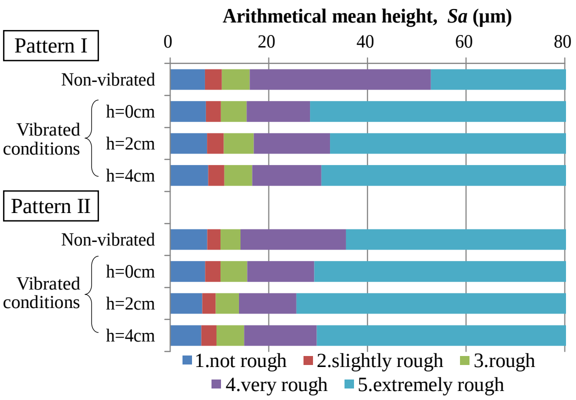


Figure 16 – Scales of roughness sensations. (Arithmetical mean height, *Sa*)

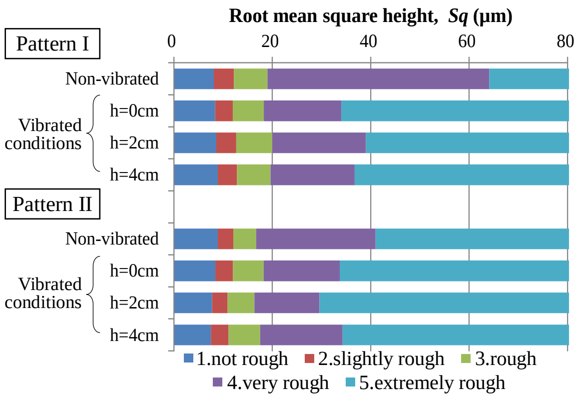


Figure 17 – Scales of roughness sensations. (Root mean square height, *Sq*)

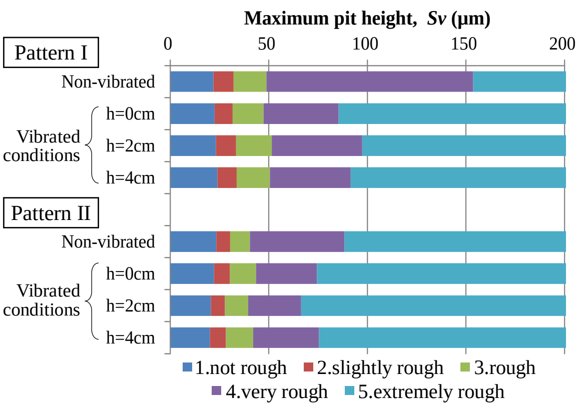


Figure 18 – Scales of roughness sensations. (Maximum pit height, *Sv*)

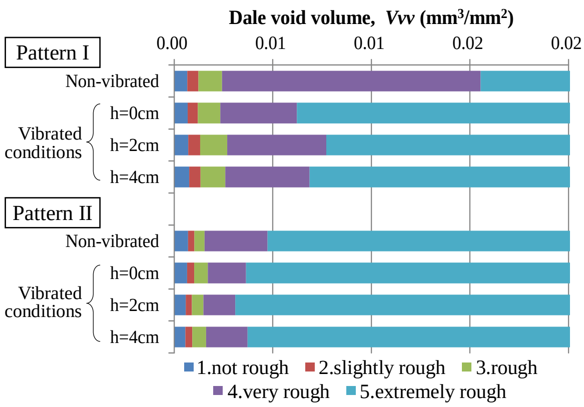


Figure 19 – Scales of roughness sensations. (Dale void volume, *Vvv*)

4. CONCLUSIONS

The roughness sensation was evaluated for two types of emboss samples to obtain design reference considered roughness sensation. As a result, the area surface texture parameter which is highly related to roughness sensation was characterized and it was indicated that the roughness sensation differed between under static condition and vibrated condition for different emboss pattern such as pattern I and pattern II. Moreover the boundary value of physical reference for the roughness sensation was obtained to indicate the design reference considered the human sense.

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