Precision Engineering 37 (2013) 433–442

Contents lists available at SciVerse ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Evaluation of the human tactile sense to microtexturing on plastic molding surfaces

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ARTICLE INFO

Article history:
Received 23 April 2012
Received in revised form 5 November 2012
Accepted 12 November 2012
Available online 29 November 2012

Keywords:
Tactile sense
Microtexture
Functional surface
Precision cutting
Vacuum hot press
Sensory evaluation
Plastic
Polypropylene
Elastomer

ABSTRACT

The purpose of this study was to develop a plastic molding with a distinguishing tactile character for various industrial applications. Grooved textures with pitches and depths ranging from several micrometers to several hundred micrometers were fabricated on plastic molding surfaces by first micromachining aluminum alloy molds, and then utilizing a vacuum hot-press procedure. The effect of texture shape on the human tactile sense was investigated by sensory evaluation and multivariate statistical analysis. The sensory evaluation revealed that tactile recognition depends on the pitch of the texture, and not on the height; an obvious change was observed at a pitch of around 100 μm. Force measurements revealed that this change in tactile response was caused by the coefficient of friction and force fluctuations.

1. Introduction

Plastic materials offer various production advantages, including moldability, high output, and low cost, and are used in various industrial applications. However, plastic has a distinctive material character in regard to the visual and tactile senses, and is sometimes regarded as inferior to a metal, fabric, and other materials in this respect. Plastic surfaces are generally textured by etching on a millimeter scale to improve these material qualities. However, the improvement obtained by such conventional methods is inadequate, and thus a more effective technique is required.

Recently, there has been considerable interest in a variety of new functional surfaces that are induced by micro- or nanoscale surface structuring, and have emerged as a result of continuing progress in micro- and nanofabrication technologies [1]. These techniques can be used to control various surface functions, including tribological [2–4], optical [5], and material properties [6], and have been studied extensively. As regards everyday human usage, functional surfaces have been successfully applied to bathroom floors and arm rails to prevent slipping [7]. However, there are a few reports on the tactile character of functional surfaces.

In studying the tactile character of small structures, several attempts have been made to determine the effect of blasted surfaces or small, randomly shaped grains on human senses [8,9]. However, the effect of arbitrary texture shapes, ranging from several micrometers to several hundred micrometers, has not been studied. For precise control of tactile sense, functional surfaces should be utilized.

The purpose of this study was to develop a plastic molding with a distinguishing tactile character for various industrial applications and to propose its evaluation method. We applied microstructures ranging from several micrometers to several hundred micrometers to plastic molding surfaces, and investigated the effect of texture shape on the tactile sense. Precision machining and a vacuum hot-press method were used to fabricate the microstructures on the plastic surfaces. The effect of texture shape on the tactile sense was investigated by sensory evaluation and multivariate statistical analysis. The surfaces were also examined in terms of force measurements while the textures were being rubbed.

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http://dx.doi.org/10.1016/j.precisioneng.2012.11.006

Table 1
Specifications of the textures used for the sensory evaluation.

Sample No.	Pitch (μm)	Height (μm)
1	Non-textured	
2	10	5
3	40	20
4	80	40
5	120	60
6	160	80
7	200	100
8	300	150
9	400	200
10	120	40
11	200	40
12	400	40
13	400	20
14	400	100

2. Fabrication of textures on plastic moldings

Plastic moldings (35 mm × 35 mm × 1 mm) with grooved textures were used in the experiments. The texture size ranged from several micrometers to several hundred micrometers. The materials used for the plastic moldings were polypropylene (PP) and elastomer, which have different characteristics. PP and elastomer have respective hardnesses of HDD61 and HDA70. PP is harder than elastomer, and elastomer has large deformability like rubber. Aluminum alloy A2017 was used for the molds because of its free machinability for texture fabrication, rather than its wear resistance. The textures were fabricated by transcription from the aluminum molds to the plastic materials.

Fig. 1 shows a diagram of the fabrication process used to create the textures. The textures were fabricated by ultra-precision cutting and a vacuum hot-press method. The aluminum mold material was mounted on an ultra-precision cutting machine (FANUC Corporation, ROBONANO α-0*i*B) with shuttle unit model B, and a mirror-finished surface was prepared using an R-shaped tool. The resulting surface roughness was $Rz = 0.04$ μm. The surface was machined via a high-speed shaper technique, using a single-crystal diamond tool with an apex angle of 90°, at a cutting speed of over 130 m/min. In this way, a grooved texture was fabricated on the aluminum mold surface, as shown in Fig. 1(b). The machined mold and plastic pellets were mounted in a vacuum hot-press machine (Imoto Machinery Co., Ltd., IMC-199A), and evacuation commenced. After evacuation was completed, the texture on the mold was transcribed to a plastic surface by vacuum hot pressing (Fig. 1(c)), and a plastic molding with a grooved texture was fabricated after demolding (Fig. 1(d)).

Table 1 lists the texture shapes fabricated in this study. Fourteen species of textures with various pitches and heights were fabricated. The minimum and maximum texture pitches were 10 μm and 400 μm, respectively. Sample 1 had a non-textured surface, fabricated by transcribing the pre-treated surface described in Fig. 1(a). Samples 2–9 had continuous grooved textures. In each of these samples, the texture shape was determined by the tool shape, and the resultant texture pitch was twice as long as the height. Samples 4 and 10–12 had various texture pitches with a constant height of 40 μm. Samples 9 and 12–14 had various texture heights with a constant pitch of 400 μm.

Fig. 2 shows a mold and plastic moldings fabricated by ultra-precision cutting and vacuum hot pressing. A grooved texture with a pitch of 40 μm and height of 20 μm (Sample 3) was fabricated on the mold surface, as shown in the scanning electron microscopy (SEM) image of Fig. 2(b). The top and bottom angles were both 90°, due to the tool shape. The cross-sectional images of the PP molding, shown in Fig. 2(c) and (d), indicate that the texture shape was successfully transcribed from the aluminum mold surface to the plastic molding surface. The shape was also successfully transcribed to the elastomer surface, as shown in Fig. 2(e). These results indicate that this method can be used to accurately fabricate texture shapes on both types of plastic.

Fig. 3 shows cross-sectional SEM images of PP moldings with various texture shapes. A flat shape was fabricated on the non-textured surface, as shown in Fig. 3(a). The surface roughness was less than $Rz = 0.1$ μm, but somewhat greater than that of the aluminum mold surface. Fig. 3(b) shows a continuous texture with a pitch of 400 μm and a height of 200 μm. The texture size was larger than that of the plastic moldings shown in Fig. 2(c) and (d). Fig. 3(c) and (d) show cross-sectional images of discontinuous textures. Samples 10–14 had discontinuous textures, and thus there were flat areas between the convex structures. In addition, the texture sizes in Fig. 3(b) and (d) were significantly different, even though the texture pitch was constant.

3. Sensory evaluation

3.1. Experimental procedure

To investigate the effect of texture shape on the tactile sense, a sensory evaluation was conducted using the fabricated plastic moldings by applying the semantic differential (SD) method with a seven-point scale [10], which is widely used in psychology. The pairs of adjectives used in the test are shown in Fig. 4. The Japanese words used in the test are shown in Fig. 4, written in Roman characters, with English translations given in parentheses. Ten pairs of adjectives were used, describing texture shapes (Uneven, Coarse, etc.), material properties (Hard, Cold, etc.), and human emotions (Comfortable and Liked).

In the test, the plastic moldings were mounted in a box to conceal them from view, since the visual sense strongly affects the tactile sense [10]. The subjects did not see the moldings either before or during the test. The plastic moldings and finger were cleaned before the test to remove contamination because the surface characteristics affect the tactual sense. The subjects were 23 Japanese men and women, whose ages varied from the teens to the sixties. Each subject was asked to record his/her feelings on an answer sheet after rubbing the molding with his/her index finger, and then check an appropriate number on each line of the sheet. Entire samples were rubbed prior to the test, to determine the tactile sense distribution, and then the test was started. The rubbing direction was perpendicular to the texture direction (transverse direction in Fig. 2(c)). Sample 7 was selected as the reference sample. It was always rubbed before rubbing the other samples, and compared with them to prevent any bias from shifting during the test. The rubbing order was set at random to remove any bias concerning the texture shape. The PP and elastomer samples were tested separately. The entire test was conducted in a limited period of time to remove the effect of environment (humidity and temperature) because these parameters would affect tactual sense.

3.2. Results and discussion

3.2.1. Factor analysis

Multivariate analysis (a statistical technique) is employed when there are several variables. In this study, factor analysis (a multivariate analysis procedure) was used to analyze corrected data. Factor analysis is a method of analyzing the relevance of each variable and extracting the factors affecting all variables in common. By applying this technique, a number of variables can be described in terms of fewer factors. Here, the factor analysis was conducted using the commercial software Ekuseru-Toukei 2010 (Social Survey Research Information Co., Ltd.).