

Effect of Thermal Shrinkage of Extruded Sheet on Mouthguard Thickness: Influence of Model Undercut

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Abstract

The effectiveness and safety of the mouthguard are greatly affected by its thickness. The aim of this study was to investigate the effect of thermal shrinkage of the extruded sheet on the mouthguard thickness depending on the amount of undercut of the model. Mouthguard sheet was used a 4.0 mm thick ethylene-vinyl acetate resin manufactured by extrusion molding. The sheets were placed in the vacuum forming machine with the sheet extrusion direction either vertical (condition V) or parallel (condition P) to the model's centerline. The working models were three hard plaster models trimmed so that the angles of the anterior teeth to the model base were 90°, 100°, and 110° (Models A, B, and C). The sheet was softened until it sagged 15 mm, and then suction was continued for 30 s. Measurement points of the mouthguard were the incisal portion (incisal edge and labial surface) and molar portion (cusp and buccal surface). The differences in the reduction rate of the thickness due to model form and extrusion direction were analyzed using two-way ANOVA and Bonferroni's multiple comparison tests. Differences in thickness depending on the extrusion direction of the sheet were observed in Models B and C on the labial surface and in all models on the buccal surface, and the thicknesses obtained under condition P were significantly thinner than those obtained under condition V. The thicknesses of the incisal edge and the cusp were not affected by the extrusion direction. The result of this study was suggested that the labial and buccal thickness of the mouthguard was secured by placing the sheet in the extrusion direction vertical to the model's centerline. Furthermore, it was clarified that the presence of the undercut of the model tends to increase the influence of the extrusion direction of the sheet on the thickness of the mouthguard.

Keywords

Mouthguard, Extrusion Molding, Thickness, Model Angle, Undercut

1. Introduction

The effectiveness and safety of mouthguards depend on the material and thickness of the sheet [1] [2] [3]. To counter the stress and strain generated during impacts, it is necessary to provide a sufficient thickness of 3 - 4 mm on the labial and buccal sides of the mouthguard [4] [5]. For single-sheet mouthguards, a 4.0-mm-thick sheet is often used. However, because the thickness is greatly reduced by thermoforming, it is difficult to secure the thickness required for impact absorption. Laminated mouthguards reliably provide a suitable thickness, but they may not be readily available to users due to the cost and fabricating time. Therefore, various fabrication methods have been investigated to secure the thickness after formation with a single sheet [6] [7] [8].

Mouthguard sheets are manufactured by extrusion or injection molding. Most of the sheets of ethylene-vinyl acetate resin (EVA), which is a mainstream product currently on the market, are manufactured by extrusion molding. Extruded sheets shrink in the extrusion direction as the strain introduced during manufacturing is released during thermoforming. This thermal shrinkage affects the mouthguard thickness depending on the sheet and model installation direction. In contrast, sheets manufactured by injection molding are not distorted during sheet manufacturing, and thus do not undergo thermal shrinkage during thermoforming [9]. Previously, the effect of the heating conditions and the shape of the sheet on the thermal shrinkage that occurs in the extruded sheet have been investigated [7].

There have been studies on the effect of model angles on the mouthguard thickness [10] [11]. These findings indicate that the presence of labial undercuts extends the mouthguard sheet and reduces labial thickness. For athletes with maxillary anterior teeth tilted to the labial side, trimming the model so that there is no undercut on the labial side tends to increase the model height. However, as the model height increases, the mouthguard becomes thinner [4] [12]. Athletes with a large overjet have a higher risk and severity of sports injuries [13] [14], indicating that the mouthguard thickness is particularly important for this type of model form. The present study was envisioned the fabrication of a mouthguard for athletes with maxillary anterior teeth tilted labially. Therefore, it was verified how much the amount of undercut in the model affected thermal shrinkage. The null hypothesis was that the thermal shrinkage of the sheet was not affected by the model form.

2. Materials and Methods

The working model was fabricated using a silicone rubber (Correcsil, Yamahachi Dental Mfg., Co., Aichi, Japan) impression taken from a maxillary dental model

(D16FE-500A-QF, Nissin Dental Products Inc., Kyoto, Japan), into which dental gypsum (New Plastone, GC, Co., Tokyo, Japan) was poured [6] [7]. The plaster model was trimmed into the following forms using a model trimmer (MT-6, Morita, Co., Tokyo, Japan): 1) Model A, in which the angle of the model formed between the labial surface of the central incisor and the base of the working model was 90° with a height of 25 mm at the incisal edge of the maxillary central incisor and a height of 20 mm at the mesiobuccal cusp of the maxillary first molar (*i.e.*, undercut amount on the labial side 0°); 2) Model B, in which the angle was 10° greater than in Model A with a height of 25 mm at the incisal edge of the maxillary central incisor and a height of 25 mm at the mesiobuccal cusp of the maxillary first molar (*i.e.*, undercut amount on the labial side 10°); and 3) Model C, in which the angle was 20° greater than in Model A with a height of 25 mm at the incisal edge of the maxillary central incisor and a height of 30 mm at the mesiobuccal cusp of the maxillary first molar (*i.e.*, undercut amount on the labial side 20°) (Figure 1).

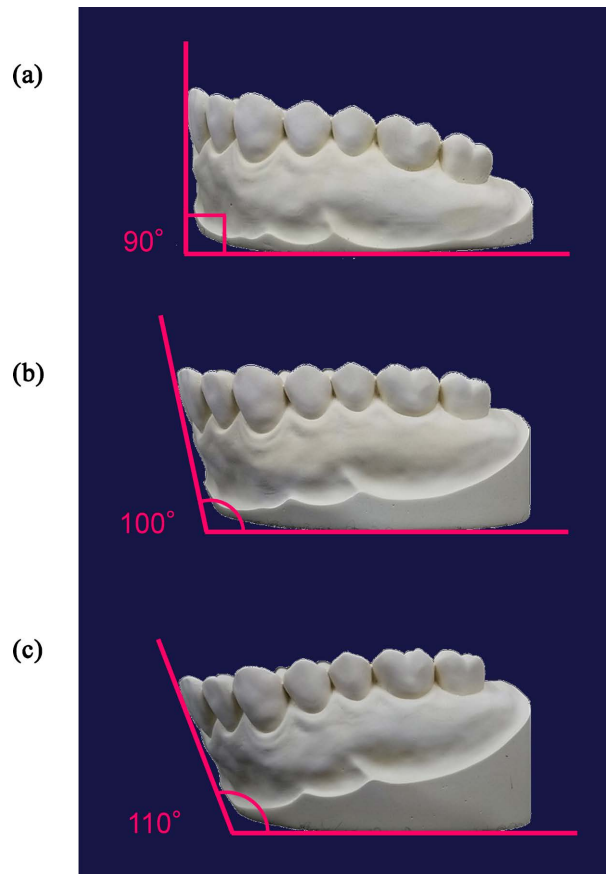


Figure 1. Working models. Angles formed between the labial surface of the central incisor and the base of the working model of (a), 90° (Model A; height of 25 mm at the incisal edge of the maxillary central incisor and 20 mm at the mesiobuccal cusp of the maxillary first molar); (b) 100° (Model B; height of 25 mm at the incisal edge of the maxillary central incisor and 25 mm at the mesiobuccal cusp of the maxillary first molar); (c) 110° (Model (c); height of 25 mm at the incisal edge of the maxillary central incisor and 30 mm at the mesiobuccal cusp of the maxillary first molar).

Mouthguards were thermoformed using EVA sheets (Sports Mouthguard, Keystone Dental Inc., Cherry Hill, NJ; $127 \times 127 \times 4.0$ mm, clear) and a vacuum forming machine (Pro-form, T & S Dental & Plastics Co., Inc., Myerstown, PA). The sheet was mounted on the forming machine so that the sheet extrusion direction was vertical (condition V) or parallel (condition P) to the model's centerline. The model position was 25 mm from the front of the forming unit. The sheet was softened until it sagged 15 mm, and then suction was continued for 30 s [6] [7]. The model was left in place for at least 24 h before the mouthguard was removed. Six specimens were formed for each condition; thus, a total of 36 mouthguards were fabricated (*i.e.*, 2 extrusion direction \times 3 model forms \times 6 repetitions).

Mouthguard thickness was measured using a specialized caliper accurate to 0.1 mm (21-111, YDM, Co., Tokyo, Japan) without a spring, so as to prevent distortion during measurement [6] [7]. The measurement points were the left and right central incisors (10 points on the incisal edge and 20 points on the labial surface) and the first molars (8 points on the cusp and 20 points on the buccal surface) [6] [7]. The measurements were taken once for each specimen.

The differences in the reduction rate of the thickness due to model form and extrusion direction were analyzed using statistical analysis software (IBM SPSS 24.0, SPSS Japan Inc., Tokyo, Japan). The Shapiro-Wilk test for normality of distribution and Levene's test for homogeneity of variance were also used. Each measurement exhibited normality and equal dispersion; accordingly, analysis was performed by two-way analysis of variance (ANOVA) and Bonferroni's multiple comparison tests. All analytical methods were performed with a significance level of 5% and a detection power of 80%, and the difference was considered significant when both were satisfied.

3. Results and Discussion

Table 1 shows the results of two-way ANOVA for the mouthguard thickness after formation. At all measurement points, the main effects of the model form and extraction direction were significant, and their interaction was also significant. Based on the results, simple main effect tests were performed prior to multiple comparisons among levels.

Table 2 and **Figure 2** show the results of multiple comparison analysis of the mouthguard thickness reduction. At all measurement sites, the rate of decrease in thickness tended to increase as the model angle increased. Differences in thickness depending on the extrusion direction of the sheet were observed in Models B and C on the labial surface and in all models on the buccal surface, and the thicknesses obtained under condition P were significantly thinner than those obtained under condition V. The thickness of the incisal edge and the cusp was not affected by the extrusion direction.

Thermal shrinkage of the mouthguard sheet occurs when the strain accumulated during manufacturing is released from the extruded sheet [9]. Because

Table 1. Results of two-way ANOVA for thickness after formation.

Source	<i>df</i>	SS	MS	<i>F</i> -value	<i>P</i> -value
Incisal edge					
Model form (A)	2	108.431	54.215	671.166	<0.001**
Extrusion direction (B)	1	53.290	53.290	659.711	<0.001**
A*B	2	9.912	4.956	61.351	<0.001**
Error	30	2.423	0.081		
Labial surface					
Model form (A)	2	291.527	145.764	2342.629	<0.001**
Extrusion direction (B)	1	30.250	30.250	486.161	<0.001**
A*B	2	2.062	1.031	16.567	<0.001**
Error	30	1.867	0.062		
Cusp					
Model form (A)	2	96.616	48.308	649.880	<0.001**
Extrusion direction (B)	1	0.640	0.640	8.610	<0.001**
A*B	2	1.807	0.903	12.152	<0.001**
Error	30	2.230	0.074		
Buccal surface					
Model form (A)	2	357.717	178.859	1719.794	<0.001**
Extrusion direction (B)	1	52.321	52.321	503.088	<0.001**
A*B	2	8.101	4.050	38.945	<0.001**
Error	30	3.120	0.104		

df: degree of freedom; SS: sum of squares; MS: mean square; ***P* < 0.01: denotes statistically significant difference.

Table 2. Results of Bonferroni's multiple comparison test according to model form.

Incisal edge				Cusp			
Condition V	Model A	Model B	Model C	Condition V	Model A	Model B	Model C
Model A				Model A			
Model B	*			Model B	n.s.		
Model C	**	n.s.		Model C	**	**	
Condition P				Condition P			
Model A				Model A			
Model B	*			Model B	n.s.		
Model C	**	n.s.		Model C	**	**	

***P* < 0.01; **P* < 0.05; n.s.: not significant.

***P* < 0.01; n.s.: not significant.

Labial surface

Condition V	Model A	Model B	Model C
Model A			
Model B	**		
Model C	**	*	

Condition P	Model A	Model B	Model C
Model A			
Model B	**		
Model C	**	**	

** $P < 0.01$; * $P < 0.05$

Buccal surface

Condition V	Model A	Model B	Model C
Model A			
Model B	**		
Model C	**	**	

Condition P	Model A	Model B	Model C
Model A			
Model B	**		
Model C	**	**	

** $P < 0.01$

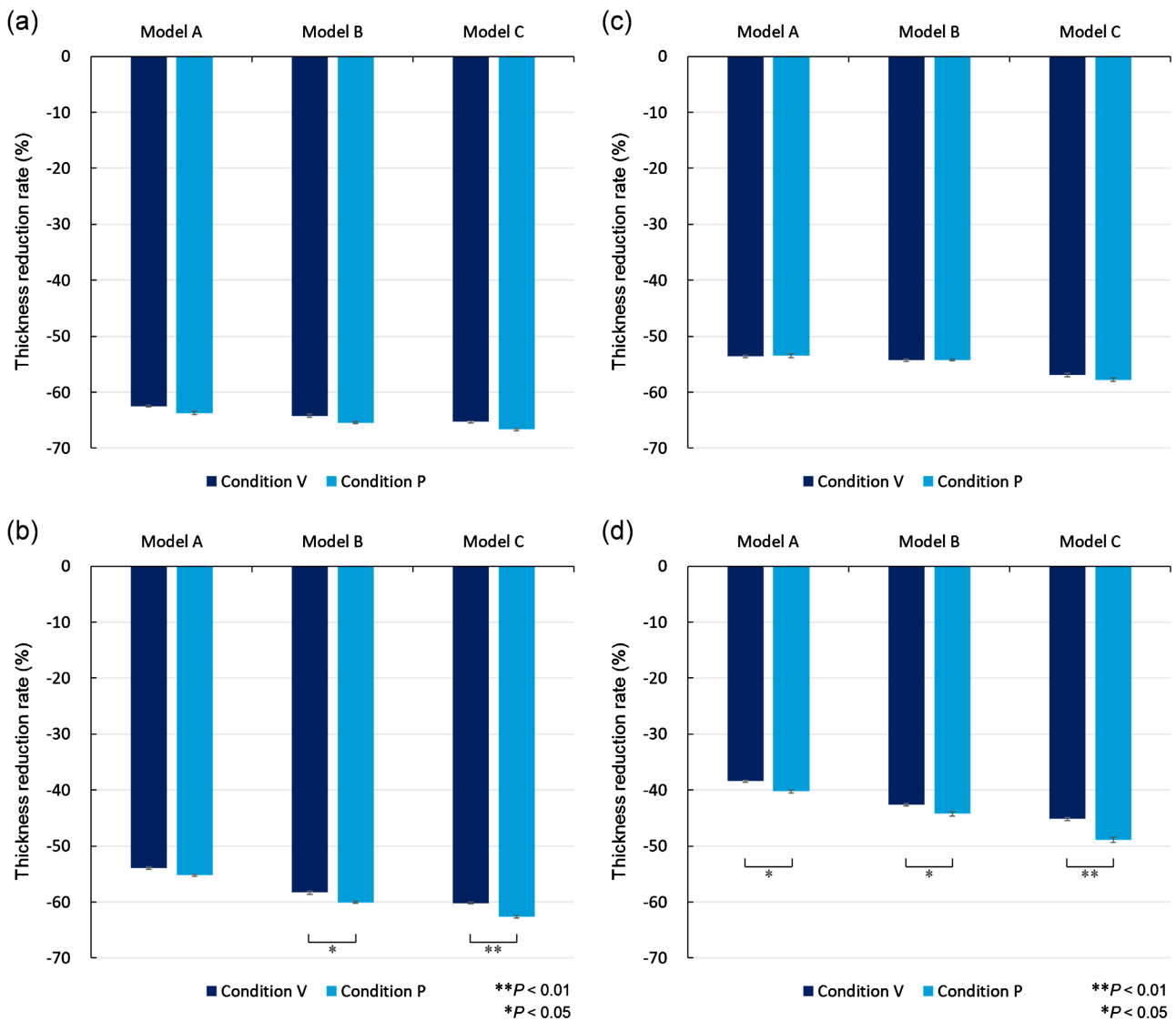


Figure 2. Mouthguard thickness at measurement points on: (a) the incisal edge; (b) the labial surface; (c) the cusp; and (d) the buccal surface. Measurements are expressed as mean value \pm SD.

thermal shrinkage occurs along the orientation direction of the sheet, the sheet shrinks in the extrusion direction. When the softened sheet is pressed against the model, the sheet is affected by the model form and has a part that extends and a part that shrinks, and thus a non-uniform shape change occurs [9] [15]. It has been reported that the mouthguard thickness is affected by factors including the model shape, the sheet material and color, and the heating conditions of the sheet [4] [11] [12] [16] [17]. However, the extent of the effect of thermal shrinkage due to the extrusion direction of the sheet on the mouthguard thickness has not been clarified for different model forms. The model form in this study was based on Model A, which has no undercut on the labial side and the height is reduced as much as possible [6] [11] [15] [17]. Models B and C were prepared by adjusting the height of the molars so that the central incisor tooth axis was tilted 10° and 20° more than Model A, respectively, and the amount of undercut on the labial side was increased.

As a result of this study, the effect of thermal shrinkage of the sheet on the mouthguard thickness differed depending on the amount of the model undercut. Therefore, the null hypothesis was rejected.

The thickness of the mouthguard on the anterior part tended to decrease as the model angle (*i.e.*, the amount of undercut) increased. This is consistent with previous studies [10] [11] showing that changes in model angle affect thickness. During model pressure welding, the sheet is fixed by the part in contact with the incisal edge and the part held by the sheet frame is stretched in the direction of the model immediately by subsequent suction or pressurization [9]. That is, if there is an undercut, the stretching in the direction of the model is large, and the mouthguard labial side tends to be thin [9]. At the incisal edge, there was no significant difference depending on the extrusion direction of the sheet, but condition P tended to increase the rate of decrease in thickness. Under condition P, the labial surface was significantly thinner in Models B and C. Because the anterior-posterior width of the model anterior part is narrow, the softened sheet can stretch greatly in the anterior-posterior direction during pressure welding [18]. The direction perpendicular to the extrusion direction has a smaller effect on the thickness of the material resin than that of parallel [19]; thus, the thickness obtained under condition P was smaller than that obtained under condition V.

The molar thickness of the mouthguard tends to decrease as the model angle increases. The model in this study had a morphology in which the molars became higher as the angle increased, similar to previous studies [4] [12], in which the mouthguard became thinner as the model height increased. In the present study, as the height of the model increased, the effect of the extrusion direction of the sheet on the buccal thickness of the mouthguard increased. The molar part of the model has a wide lateral width in addition to the anterior-posterior width, and thus the softened sheet stretches in the left-right direction as well as in the anterior-posterior direction during pressure welding [18]. The direction perpendicular to the extrusion direction has a small effect on the thickness of the

material resin, whereas the direction parallel to the extrusion direction has a large effect on the thickness [19]. Therefore, it was inferred that the decrease in thickness due to a slight extension was larger under condition P than condition V, similar to the anterior part.

4. Conclusion

The form of the working model, especially the presence of undercuts on the labial side, affects the labial thickness of the mouthguard during thermoforming. In cases where the height of the model increases by trimming to reduce the amount of undercut (*i.e.*, the labial side of the anterior teeth of the upper jaw is tilted), it was clarified that it is effective in suppressing the decrease in the labial and buccal thicknesses of the mouthguard by placing the sheet in the extrusion direction perpendicular to the model's centerline. However, this method did not secure the mouthguard thickness required for shock absorption. To maintain an appropriate thickness, it is essential to devise a forming method and laminated mouthguards will be considered in future work.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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