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Research article

Synthetic Badminton Shuttlecocks: Study and Prototype

Quang-Phuoc Tran[1], Quoc-Chi Nguyen[1], Trong-Khuyen Nguyen[2], Phuong-Tung Pham[1], Duy-Anh Nguyen[1]

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ABSTRACT
In today's world, with the rapid advancement of industrialization, the livestock sector has become increasingly reliant on scientific and technological innovations in engineering practices. This dependency is even more apparent in the poultry meat industry, a sector known for yielding high economic returns. Given the rising market demands, the industry is constantly striving to minimize the raising period without compromising the integrity and quality of the meat. However, this accelerated growth effort has profound implications for the support industries that directly rely on poultry by products, particularly feathers. In the case of ducks, a reduced growth period may indeed impede feather development, which presents significant challenges for their utilization in technically demanding sectors. Notably, the manufacturing of badminton shuttlecocks, which traditionally relies on high-quality duck feathers, faces a potential material constraint issue. To address this pressing concern, this proposal advocates for the artificialization of the shuttlecock's feathers. This innovative solution aims to circumvent the material constraints posed by the changing livestock industry, while still ensuring the production of high-quality shuttlecocks. The study employed advanced simulation techniques, utilizing Moldflow software integrated with the finite element method and boundary element method, to identify potential defects and optimize the design. Following the simulations, process parameters were meticulously determined for the design and fabrication of the injection mold. The result was an efficient and effective method for producing artificial feather shuttlecocks, which maintains the quality standards of traditional models. This article presents a comprehensive analysis of the plastic injection-molded shuttlecock body product. It provides a detailed description of the engineering process, the challenges faced, the solutions developed, and the results of the rigorous testing process. It is our hope that this research will spur further innovation in the field, paving the way for a more sustainable and adaptable shuttlecock manufacturing industry.
Key words: Micro Molding, Synthetic Badminton Shuttlecocks, Injection Molding

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INTRODUCTION

Plastic industry is one of the world's fastest growing industries, ranked as one of the few billion-dollar industries. Almost every product that is used in daily life involves the usage of plastic and most of these products can be produced by plastic injection molding method [1]. Plastic injection molding process is well known as the manufacturing process to create products with various shapes and complex geometry at low cost [2]. The injection molding process involves the injection of a polymer melt into a mold where the melt cools and solidifies to form a plastic product.

It is generally a three phase process comprising filling, packing and cooling phases. Its popularity is typified by the numerous products produced in this way at the present time [3].

The first games important to the creation of badminton were practised in Asia 2500yr BC [4]. Soldiers played tijian-zi, which consisted of exchanging with their feet a shuttle generally made of a heavy leather ball planted with feathers [4]. Badminton is played either by two opposing players (singles) or two opposing pairs (doubles). Each player (or team) stands on opposite halves of a rectangular court which is 13.4 meters long, 5.2

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meters-wide and divided by a 1.55 meters-high net. Players score points by striking a shuttlecock with their rackets so that it passes over the net and lands in the opponent's half-court. Each side may strike the shuttlecock only once before it passes over the net. A rally ends once the shuttlecock has hit the floor or a player commits a fault [5].

Semi-Artificializing the shuttlecock's body is playing an increasingly important role in protecting the environment. Synthetic shuttlecocks have advantage that they last much longer as compared to feathered shuttlecocks. Synthetic shuttlecocks have complex aerodynamics behavior than a feathered shuttlecock. They cannot move as quickly but are far better for maintaining whatever speed they gain [6]. Feathered shuttlecocks are made from the feathers of only the left wings of ducks or geese [6]. Previously, the production of shuttlecocks required a large amount of duck feathers and rubber, resulting in unnecessary waste and environmental pollution. Improvements in the artificialization of shuttlecock production have significantly reduced this waste. Manufacturers now use friendly materials to produce shuttlecocks, increasing product sustainability and protecting the environment. Furthermore, this provides athletes with a better playing experience.

3D MODEL FOR THE BODY OF SHUTTLECOCK

The detailed drawing of the product is shown in Figure 1, and the shuttlecock body must meet the requirements for strength, weight, and flexibility. Therefore, a technical plastic material with low shrinkage coefficient was chosen. Among the available materials, PA6 B33 L09 (Polyamide 6) with shrinkage coefficient of 1.0 is a suitable material for making the shuttlecock body. The product specifications are indicated on the drawing.

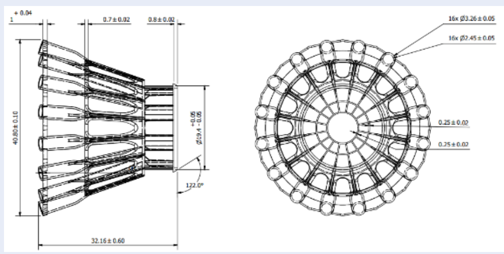

Fig. 1. Detail drawing of the body of the shuttlecock

METHODOLOGY

Simulation of processes

In this study, finite element method and boundary element method embed in Moldflow was used to identify potential defects. Then, the process parameters are established to design and manufacture the injection molding. The selected simulation parameters are:

Maximum injection pressure: 185 MPa.

By using Polyamide 6(PA6) B3L plastic material, the chosen process parameters are:

Mold temperature: 60°C.

Melt temperature: 270°C.

The filling ability is 100% and there are no defects. Time fill time is approximate 0.63s. The simulation result was showed in Figure 2.

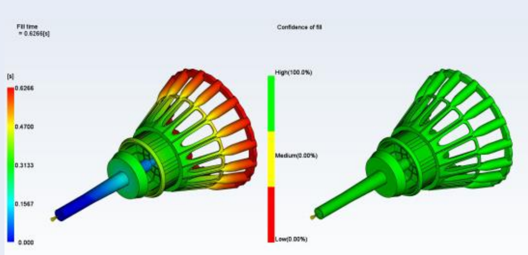

Fig. 2. Fill time and confidence of fill

Figure 3 illustrated the average temperature and pressure during injection process. The average temperature of the molding process is 278.40°C

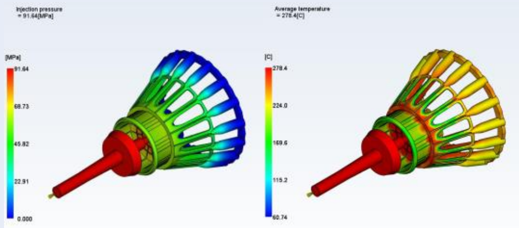

Fig. 3. Injection pressure and average temperature

The locations of the weld line and air traps were determined in Figure 4. It is the basis parameter for mold design and prediction of possible damage during injection molding.

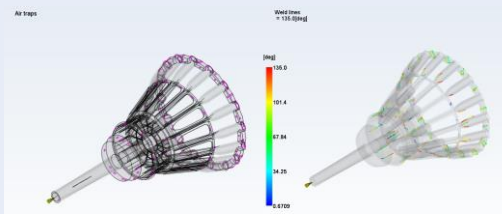

Fig. 4. Air traps and weld lines

Heat exchanger

The mold enclosure size is indicated in Figure 5.

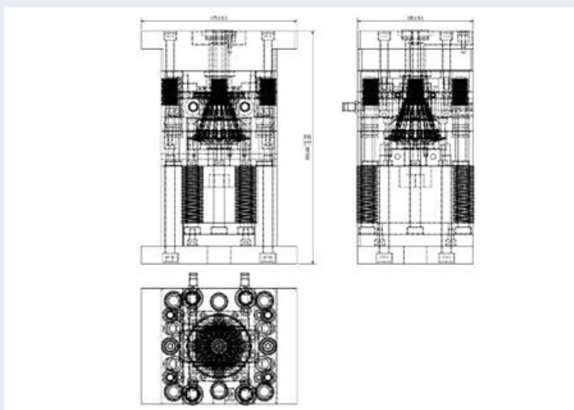

Fig. 5. The mold enclosure size

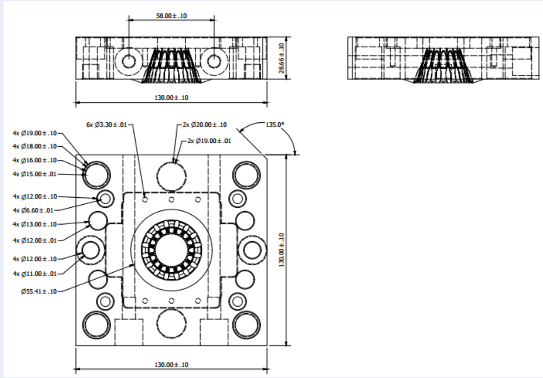

Fig. 6. Detail drawing of Cavity

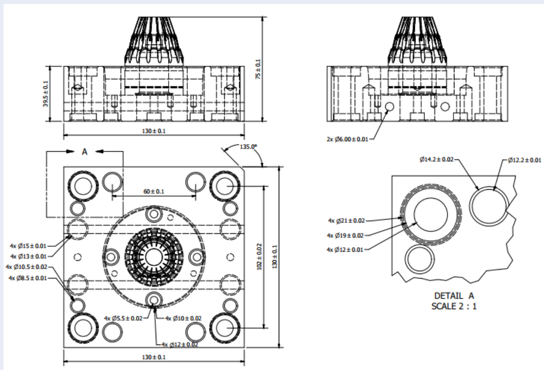

Fig. 7. Detail drawing of Core

Materials: SKD 61 steel for the cavity and core, and stainless steel for the exterior

Environment temperature: 30°C

Mold temperature: 100°C

Time to meet the needed temperature: approximately 15 minutes.

Identify an area of faces:

$$S_{1t} = 26166.175\ (mm^2)$$
$$S_{2d} = 26166.175\ (mm^2)$$
$$S_3 = 26166.130\ (mm^2)$$
$$S_4 = 175.130\ (mm^2)$$

To calculate the heat capacity required for heating the mold, the entire cubic block with the given surface area is considered. The amount of heat required to supply the mold includes the heat required to heat the mold and the heat lost due to heat exchange with the surrounding environment.

The amount of heat required to heat the mold from 30^0C to 100^0C [8] is:

$$Q_1 = G \times c_p \times \Delta t \qquad (1)$$

Corresponding to a water temperature of 100 degrees Celsius, refer to Appendix 25 [7]:

$$c_p = 4.22 kJ / kg; \Pr = 1.75$$

In which:

$$G = V \times m = 32.477\,(kg) \qquad (2)$$
$$c_p = 4.22kJ / kg;$$
$$\Delta t = 100 - 30 = 70^o C$$
$$So: Q_1 = 9593.7058kJ$$

The press machine operates in a stable temperature environment. The mold temperature is naturally transmitted through the external environment. Therefore, the heat loss to the environment is counted as natural convection.

The amount of heat loss is the total amount of heat transferred through the six surfaces of the mold to the external environment.

The amount of heat loss [2] is:

$$Q = \alpha \times S \times \Delta t \qquad (3)$$

Coefficient Gr [2]:

$$G_r = \frac{g\beta\Delta t L^3}{v} \qquad (4)$$

Refer to Appendix 22 [7]. Physical parameters of dry air corresponding to t = 30°C (H=760mmHg): $v = 16 \times 10^{-6} m^2 / s$

Some parameters:

$$g = 9.81 m / s^2$$
$$\beta = \frac{1}{t + 273} = \frac{1}{303} \qquad (5)$$
$$\Delta t = 100 - 30 = 70^o C$$

Surfaces S_1, S_2: Pick L = 175 mm (small size convention). So: $Gr_n = 759.134$

Surfaces S_3, S_4: Pick L = 130 mm convention for choosing height size). So: $Gr_n = 311.196$

According to Rayleigh [8]:

$$Coeficient\ Ra = Gr \times \mathrm{Pr} \qquad (6)$$

Refer to Appendix 22 [7]: $\mathrm{Pr} = 0.701$

So: $Ra_1 = 532.153; Ra_3 = 218.149$

$$\alpha = \frac{Nu \times \lambda}{L} \qquad (7)$$

Refer to Appendix 22 [7]: $\lambda = 2.7 \times 10^{-2} \frac{W}{m}$

Natural convection heat dissipation coefficient [8]:

$$Nu = CRa^n \qquad (8)$$

Refer to Appendix 10.1 [7] corresponding to Ra:

$n = 0.25; C = 0.54$

With: $Nu_{2d} = Nu_{2t} = 2.59$

$Nu_3 = Nu_4 = 2.459$

So: $\begin{aligned}\alpha_{2d} &= \alpha_{2t} = 0.3996 \\ \alpha_3 &= \alpha_4 = 0.511\end{aligned}$

The heat released by the surfaces [8]:

$$Q = \alpha S \Delta t \tag{9}$$

So:

$$\begin{aligned}
Q_1 &= \alpha_{2d} \times S_{1t} \times \Delta t = 1.281 kJ \\
Q_2 &= \alpha_{2t} \times S_{2d} \times \Delta t = 1.281 kJ \\
Q_3 &= \alpha_4 \times S_3 \times \Delta t = 1.217 kJ \\
Q_4 &= \alpha_3 \times S_4 \times \Delta t = 0.814 kJ
\end{aligned}$$

Heat loss through 6 faces:

$$\begin{aligned}
Q &= \sum Q_i \\
Q &= 1.281 + 1.281 + 2 \times 1.217 + 2 \times 0.814 = 6.624 kJ
\end{aligned}$$

Total heat required to provide:

$$\begin{aligned}
Q &= Q_{tt} + Q_{ct} = 6.624 + 9592.7058 \\
Q &= 9600.3298 kJ
\end{aligned}$$

Select the mold heating time from 30^{0}C up to 100^{0}C is 15 minutes.

The required thermistor power:

$$P = \frac{Q}{t} = 9600.3298 = 10.667 kW \tag{10}$$

Therefore, the capacity of the heating resistor for the mold to be 12 kW is suitable.

Slider

When calculating the distance for the slide core to determine the angle of inclination for the slide, it is important to ensure that the sliding portion of the core does not extend beyond the parting line and can still be easily extracted from the mold.

The angle pin is one of the most common systems used to act on the side core, used to pull the side core for a certain distance depending on the height of the side core. During the mold closing stage, the angle pin pushes the side core inward. The displacement of the side core is determined by the working length and angle of the angle pin cam.

$$M = (L \sin \alpha) - \left(\frac{C}{\cos \alpha} \right) \tag{11}$$

So:

$$\begin{aligned}
L &= \frac{M + \dfrac{C}{\cos \alpha}}{\sin \alpha} = \frac{M \times \cos \alpha}{\sin \alpha \times \cos \alpha} \\
&= \frac{8 \times \cos 10^o}{\sin 10^o \times \cos 10^o} = 46.07 (mm)
\end{aligned}$$

In which:

L: the length of the angle pin

M: Slide motion distance

α : inclination angle of angle pin (10 – 25 degrees)

C: clearance between angle pin and sliding plate

D: motion distance $d = \dfrac{c}{\sin\alpha}$

Additionally, the Q angle must be greater than $\alpha + 5^0$ to ensure that during mold closing, the angle pin can easily be inserted into the inner core.

RESULTS AND DISCUSSION

The clamping force of the mold must be large enough to ensure that the mold is always tightly closed. If the force is smaller than the injection pressure of the plastic, the movable mold half will be pushed back during the molding process, resulting in flash and deformed parts that do not meet the requirements.

As there is only one cavity in the mold, the clamping force can be calculated using the following formula:

$$F_K = K \times S \qquad (12)$$

K clamping force constant PA6 is:

$$0.9\,GPa = 900\,MPa = 900 \times 10^6\,N/m^2$$

We have:

$$F_K = K \times S = 90 \times 228.3551 = 20551.959N$$

An injection molding machine with clamping forces of 25 or 30 tons could have been chosen, but due to the economic constraints in the workshop, a machine with a clamping force of 60 tons in Figure 8 is selected to use.

The following are the parameters of the injection molding machine used in the experiment: Maximum clamping force: 60 tons; Maximum injection pressure: 185 bar; Injection rate: 87g/s

Fig. 8. NISSEI 60-ton injection molding machine

Experiment to quantify plastic: Mold temperature 50°C; Plastic injection temperature: 250°C; Injection pressure: 140Mpa.

Fig. 9. Simulation and result for experiment 1

The result in Figure 9 is compatible with the filling simulation at 80% so the volume of plastic will be increased continuously.

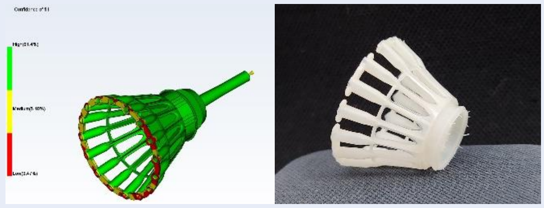

Fig. 10 Filling and molding simulation for experiment 2

The result in Figure 10 is compatible with the filling simulation at 90% but the volume of plastic will be increased continuously.

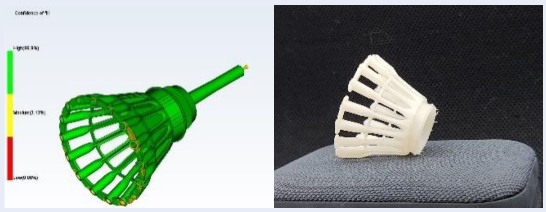

Fig. 11. Simulation and result in experiment 3

It is compatible with the filling simulation at 99%. Although the product has achieved its appearance, the volume of plastic will be increased to boost the quantity of plastic. The result was shown in Figure 11.

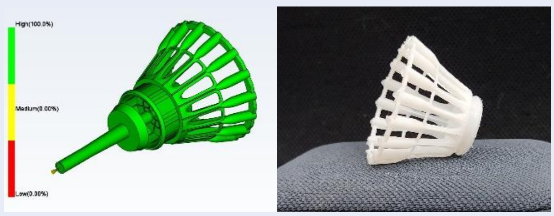

Fig. 12. Simulation and result in experiment 4

In Figure 12, after increasing the amount of plastic, a significant improvement in the cosmetic appearance of the product has been observed, which is smoother and shinier.

The dimensions of the shuttlecock body will be measured. Measurements on the technical drawing are conducted 3 times on the actual product and the results are presented in Table 1. The x_i dimension is smaller than the required size on the drawing so the dimensions of the product meet the size requirements of the drawing.

Table 1: Measurement result

No	Dimension	1st	2nd	3rd	$\bar{x}$	σ	$x_i = \bar{x} \pm 3\sigma$	Conclusion
1	$40.8^{+0.1}_{-0.1}$	40.81	40.75	40.70	40.753	0.057	40.753 ± 0.057	Achieved
2	$32.16^{+0.6}_{-0.6}$	32.11	32.15	32.10	32.12	0.03	32.12 ± 0.03	Achieved
3	$1.02^{+0.02}_{-0.02}$	1.02	1.01	1.01	1.013	0.007	1.013 ± 0.007	Achieved
4	$0.7^{+0.02}_{-0.02}$	0.71	0.70	0.70	0.703	0.007	0.703 ± 0.007	Achieved
5	$0.8^{+0.02}_{-0.02}$	0.79	0.81	0.81	0.803	0.013	0.803 ± 0.013	Achieved
6	$3.26^{+0.05}_{-0.05}$	3.25	3.27	3.25	3.257	0.013	3.257 ± 0.013	Achieved
7	$2.45^{+0.05}_{-0.05}$	2.45	2.44	2.44	2.443	0.007	2.443 ± 0.007	Achieved

CONCLUSION

In this article, a detailed analysis of the plastic injection molded shuttlecock body product, including both description and results of the testing process is presented. Moreover, some basic characteristics of the injection mold design are introduced to provide a comprehensive overview of the production process for this product.

CONFLICT OF INTEREST

The authors want to reiterate that there are no known conflicts of interest related to this publication. Furthermore, there hasn't been any substantial financial backing for this project that could have influenced its findings.

AUTHOR'S CONTRIBUTION

All authors conceived of the study and participated in its design and coordination and helped to draft the manuscript. The authors read and approved the final manuscript.

Quang-Phuoc Tran : designed the study and wrote the manuscript

Quoc-Chi Nguyen : designed the study and analyzed the results

Trong-Khuyen Nguyen : collected the data and analyzed the results

Phuong-Tung Pham : collected the data and analyzed the results

Duy-Anh Nguyen : analyzed the results and wrote the manuscript

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Bài báo nghiên cứu

Quả cầu lông nhân tạo: Nghiên cứu và tạo mẫu

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TÓM TẮT
Ngày nay, cùng với sự tiến bộ vượt bậc trong lĩnh vực công nghiệp hóa, ngành chăn nuôi cũng đang ngày càng phụ thuộc vào các thành tựu khoa học công nghệ cũng như các phương pháp kỹ thuật tiên tiến. Sự phụ thuộc này trở nên rõ ràng hơn đặc biệt trong ngành công nghiệp thịt gia cầm, lĩnh vực mang lại lợi nhuận kinh tế cao. Do nhu cầu của thị trường ngày càng tăng, ngành công nghiệp gia cầm đang cố gắng đẩy mạnh sản lượng thông qua việc rút ngắn chu kỳ chăn nuôi nhưng không làm giảm chất lượng thịt đầu ra. Tuy nhiên, nỗ lực tăng trưởng này lại có ảnh hưởng sâu sắc đối với các ngành công nghiệp phụ thuộc trực tiếp vào sản phẩm gia cầm, đặc biệt là lông vũ. Trong trường hợp của vịt, việc giảm thời gian tăng trưởng có thể cản trở sự phát triển đầy đủ của lông vũ, điều này đặt ra thách thức đáng kể cho việc sử dụng nó trong các lĩnh vực đòi hỏi kỹ thuật. Đáng chú ý ở đây là sản xuất cầu lông, theo truyền thống phải dựa trên nguồn lông vũ chất lượng cao, giờ đang phải đối mặt với nguy cơ hạn chế nguồn nguyên liệu đầu vào. Để giải quyết mối quan tâm cấp bách này, nhóm tác giả nghiên cứu đề xuất phát triển lông nhân tạo một phần để thay thế cho lông vũ tự nhiên trong sản xuất quả cầu lông. Giải pháp sáng tạo này nhằm mục đích phá vỡ những hạn chế về vật liệu do ngành chăn nuôi đang thay đổi gây ra, trong khi vẫn đảm bảo sản xuất những quả cầu lông chất lượng cao. Nghiên cứu sử dụng các kỹ thuật mô phỏng tiên tiến, sử dụng phần mềm Moldflow tích hợp với phương pháp phần tử hữu hạn và phương pháp phần tử biên, để xác định các khuyết tật tiềm ẩn và tối ưu hóa thiết kế. Sau khi mô phỏng, các thông số quy trình được xây dựng một cách tỉ mỉ để thiết kế và chế tạo khuôn phun. Kết quả nghiên cứu đưa ra một phương pháp hiệu quả để sản xuất quả cầu lông nhân tạo nhưng vẫn đạt được các tiêu chuẩn chất lượng của các sản phẩm truyền thống. Bài viết này trình bày phân tích toàn diện về sản phẩm thân quả cầu được ép bằng nhựa. Nó cung cấp mô tả chi tiết về quy trình kỹ thuật, những thách thức phải đối mặt, các giải pháp được phát triển và kết quả của quy trình thử nghiệm nghiêm ngặt. Chúng tôi hy vọng rằng nghiên cứu này sẽ thúc đẩy sự đổi mới tiếp theo trong lĩnh vực này, mở đường cho một ngành sản xuất cầu lông bền vững và dễ thích nghi hơn.

Từ khoá: Công Nghệ Phun Ép Nhựa, Vi Khuôn, Quả Cầu Lông Nhân Tạo

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