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Optimization of Injection Molding Simulation of Bioabsorbable Bone Screw Using Taguchi Method and Particle Swarm Optimization

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Abstract

Application of metal bone screws for internal fixation has many risks, including infection, temperature sensitivity, and radiologic imaging disturbance. Bioabsorbable bone screws appear to overcome the disadvantages of metal bone screws. Many researchers have developed numerous bioabsorbable bone screws using various kinds of polymers. In this research, polylactic acid (PLA) and polyglycolic acid (PGA) were used as the materials for the bone screw. The injection molding method was used to produce the screws as it is one of the most effective methods in polymer or plastic production. This study aims to understand the effect of injection molding simulation parameters on shrinkage and warpage of bone screw, and to discover the best parameters combination to obtain optimal responses, and compare PLA and PGA bone screws. Injection molding simulation experiments used the Taguchi method, and the optimization process used particle swarm optimization. The results showed that melt temperature, injection time, and packing time had significant effects on shrinkage and warpage of PLA bone screws. Meanwhile, the significant factors for PGA bone screws were mold temperature, melt temperature, and injection time. After the optimization process, the shrinkage and warpage value improved to 2.4233% and 0.0928 mm for PLA bone screws and 8.9592% and 0.4646 mm for PGA bone screws.

Keywords: Bone screw, injection molding simulation, Taguchi, PSO.

1. Introduction

Several bone fracture fixation methods are used to aid the healing process, including the conventional method, external fixation, and internal fixation. From these methods, the most commonly used one is internal fixation using a metal implant. The advantages of this method include reduction of malunion and nonunion risk of broken bones, shortening ofthe length of stay in a hospital, and increasing the rate of recovery. One of the various kinds of implant used for internal fixation is bone screw. Bone screw as an independent implant is usually applied on femoral neck fracture, femoral head dislocation, distal femur fracture, tibial plateau fracture, and also on cure ankle, elbow, and shoulder fracture [1]. This screw is usually made of metal, such as stainless steel, titanium, or cobalt, and has to be removed after recovery throughout the surgical process. The risks involved in this process include atrophy, infection, and bone complication due to discharge of metal ions [2]. Furthermore, the application of metal as bone screw material has some disadvantages, such as temperature sensitivity, growth disturbance in children [3] and also disturbing radiologic imaging [4].

Because of the disadvantages of metal bone screws, several researchers have attempted to develop a bioabsorbable bone screw that is degradable inside the human body over time [5]. This kind of bone screw is advantageous because it does notinvolve any surgical process for its removal. It also does not disturb radiologic imaging owing to the characteristic of the material used, which can be passed through X-ray [6]. Bioabsorbable bone screw is usually made of a biodegradable polymer such as polylactic acid (PLA), polyglycolic acid (PGA), polylactic-co-glycolic acid, polycaprolactone (PCL), and polydioxanone PDS [7].Additionally, previous studies proved that the screw has good osseointegration and excellent biocompatibility based on in vivo evaluation [8]. Their study showed that the strength retention of the screws is sufficient for safe fixation [9].

One of the various methods that can be used to produce bioabsorbable bone screws is injection molding. This method is widely applied in polymer and plastic industries because ofthe highly accurate products with fast cycle time. It is also one of the most important polymer-processing operations in plastic industries [10]. Nevertheless, some parameters, such as melt temperature, pressure limit, packing time, injection pressure, injection speed, injection time, cooling time, and mold temperature,must be considered, which affect the result of injection molding. A bad setting of these parameters will lead to a defective product because of shrinkage and warpage [11]. Thus, this study aimed to investigate the best parameter combination that yields a minimum shrinkage and warpage value. Moreover, the effect of these

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parameters was analyzed toward the shrinkage and warpage value and compared between PLA and PGA bone screws.

Several studies have been conducted by some researchers to obtain an optimal parameters combination of injection molding. These studies focused on different parameters of injection molding, and the result varied on the material, dimension, and shape of products. Several parameters, that is, the effect of melt temperature, mold temperature, injection speed, injection time, cycle time, packing time, packing pressure, and coolant temperature, have been investigated [12, 13, 14].

Moreover, different optimization methods were used in optimizing the injection molding process. Kiatcharoenpol [15] and Othman [16] used the Taguchi method to optimize their injection molding results, such as shrinkage, total displacement, and warpage. Conversely, several multiresponse optimization methods were utilized by some researchers to obtain simultaneous optimization results such asgray relational analysis, which was applied by Wang [10],particle swarm optimization by Abuzeid [17] and artificial neural network, which was implemented by Oliaei [18].

Various studies of optimizing shrinkage and warpage of a product have been conducted. Nevertheless, studies on the optimization of the bioabsorbable bone screw injection molding process are still limited. Thus, this study aims to investigate the optimal parameter combination of injection-molded bone screws to obtain minimum shrinkage and warpage. Additionally, this study compared PLA and PGA bone screws in terms of injection molding quality or mechanical strength. This study also aims to understand the effect of the parameters, such as melt temperature, mold temperature, injection time, cooling time, and packing time on the responses such as shrinkage and warpage. A modified ISO 5835:1991 cancellous bone screw with an interlocking thread system has been proposed [19].

2. Material and Method

The experiment preparation was conducted by creating a bone screw design in Autodesk Inventor Software. The design created was a 6.5 mm ISO 5835:1991 cancellous bone screw with thread modificationusing fastener thread, which can withstand multidirectional force and bending moment so it can limit the movement and radial forces of the bone screw [19]. Cancellous screws have various lengths depending on their purpose. A 75-mm-long cancellous bone screw was chosen for the design, which can be applied for Schatzker type 1 tibial plateau fracture fixation [20]. This study used two different materials for the screw such as PLA and PGA. Table 1 shows the properties of the material used in this simulation. Figure1 shows the design of the bone screw for tibial plateau fracture fixation.

The responses of this experiment are shrinkage and warpage of injection-molded bone screw. These responses were chosen because they are the common defects that affect the quality of the injection-molded part [21]. This study used five factors, namely, melt temperature, mold temperature, injection time, cooling time, and packing time. Table 2 shows the levels of each factor. This study used the Taguchi method for the experiment, which was conducted on the basis of the orthogonal array [22]. This experiment used five parameters with five levels each. Thus, the orthogonal array $L_{25}(5^5)$ was chosen for the experiment.

Table 1. Properties of material

Properties	PLA	PGA
Young modulus (MPa)	3500	6500
Poisson	0.36	0.453
Shear modulus (MPa)	1287	6000
Density (kg/m^3)	1251.5	1500
Tensile strength (MPa)	60	220
Yield strength (MPa)	60	220

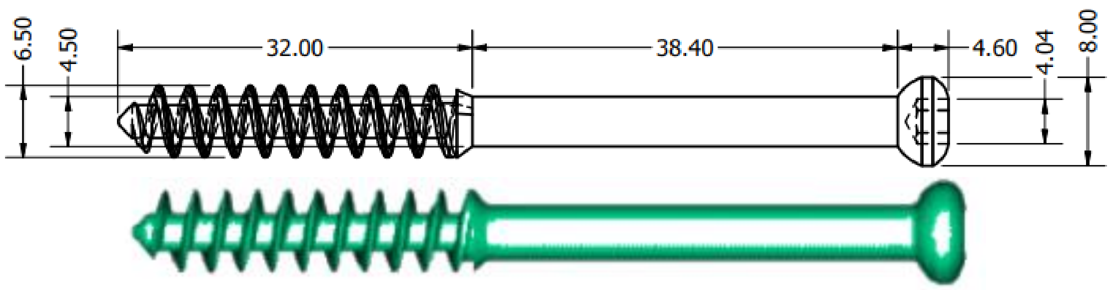

Figure 1. Bone screw design

Table 2. Factors and levels

Code	Factor	Material	Level 1	2	3	4	5
A	Mold Temperature (°C)	PLA	10	17	24	31	38
		PGA	60	85	110	135	160
B	Melt Temperature (°C)	PLA	170	185	200	215	230
		PGA	220	232.5	245	257.5	270
C	Injection Time (second)	PLA	1	1.5	2	2.5	3
		PGA	1	1.5	2	2.5	3
D	Cooling Time (second)	PLA	17	19	21	23	25
		PGA	17	19	21	23	25
E	Packing Time (second)	PLA	10	12.5	15	17.5	20
		PGA	10	12.5	15	17.5	20

An experiment was carried out using injection molding simulation software. Various kinds of injection molding simulation software have been widely used in several studies because it can reduce the cost of the experiment, such as in Wang [23], which used Moldex 3D Software for the simulation, and in Martowibowo [24], which utilized Mold Flow software. This study used Autodesk Moldflow Adviser to simulate the injection molding process on the basis of the orthogonal array. Before simulation commenced, the mold cavity of injection molding was designed. Figure2 shows the cavity mold design. This design was chosen after some trials and errors to avoid any defect due to injection location such as short shots or gate marks. After simulation, shrinkage and warpage value for each level setting was obtained. This value will be analyzed and optimized in the next step.

Shrinkage and warpage data were obtained from the simulation process. These data were analyzed using analysis of variance (ANOVA), which was used to understand the effect of factors on responses and interpretation of experimental data [25, 26]. Afterward, a regression equation was generated to predict the value of shrinkage and warpage after optimization.

This study used the particle swarm optimization (PSO) method to optimize shrinkage and warpage value. PSO is an optimization method that searches the optimal solution using an agent called particle, the track of which is controlled by deterministic and stochastic components. This method was chosen because it can solve continuous problems such as investigating optimal parameters in a machine, and it can optimize some responses simultaneously. When compared with other methods, PSO also has some advantages, such as a faster optimization process, fewer parameters used, and a maintained balance between global and local searching in its optimization process.

After obtaining the optimum value, the next stage was study validation, which was performed through experimental confirmation and mechanical simulation. Experimental confirmation was conducted to compare the optimum predicted shrinkage and warpage value from the regression equation and the simulated shrinkage and warpage using the optimal setting level. Mechanical simulation was used to understand the strength of bone screws when applied to fix the bone fracture.

Results and Discussion

Shrinkage and warpage value can be measured by choosing “Fill+Pack+Warp” analysis in Autodesk Moldflow Adviser. Table 3 shows the result of the experiment. Furthermore, the results of the experiment were analyzed using ANOVA with Minitab 17. The effect of a factor on responses can be determined based on its P-value. Table 4 presents the P-value result of each factor.

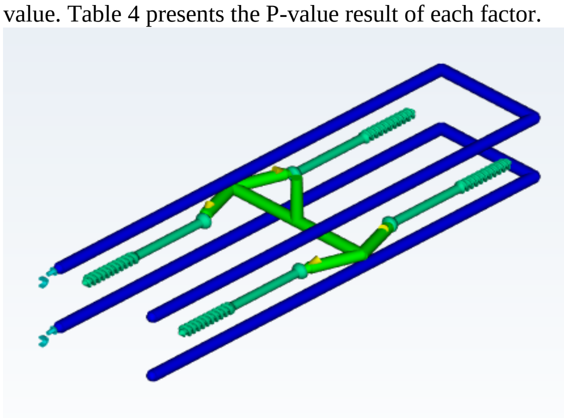

Figure 2. Cavity mold design

Table 3. Experiment results

Exp. No.	PLA		PGA	
	Shrinkage (%)	Warpage (mm)	Shrinkage (%)	Warpage (mm)
1	4.924	0.1114	9.642	0.4612
2	4.685	0.1182	10.2	0.4794
3	6.96	0.1461	10.88	0.4933
4	7.964	0.1632	12.26	0.5041
5	8.639	0.175	13.6	0.5128
6	3.077	0.1066	10.83	0.468
7	5.122	0.1201	10.89	0.4838
8	7.097	0.1484	11.39	0.4966
9	8.086	0.1652	13.12	0.5071
10	7.177	0.1503	11.76	0.5043
11	4.459	0.1118	11.62	0.4726
12	4.819	0.1211	11.59	0.4877
13	7.088	0.1485	11.72	0.5001
14	6.361	0.139	11.32	0.4978
15	9.632	0.1644	13.83	0.5099
16	2.707	0.1052	12.14	0.4779
17	6.407	0.1379	12.23	0.4926
18	6.161	0.1305	12.24	0.4897
19	7.196	0.1505	12.32	0.504
20	8.055	0.1675	13.76	0.5141
21	4.143	0.1115	12.87	0.4852
22	4.451	0.1135	10.65	0.4822
23	5.292	0.128	11.97	0.4972
24	8.218	0.1601	14.19	0.509
25	8.388	0.1735	15.41	0.5174

The results of the experiment were modeled using regression and were used to predict the shrinkage and warpage value after optimization. Furthermore, Minitab 17 was used to build the regression model. Table 5 shows the regression model.

All of the regression equations generated great R-square values,which means that the model explained the response variability well. Additionally, the differences between adjusted R-square and predicted R-square are less than 20%, indicating a strong correlation between the prediction model and simulation result [27]. The next step was optimization using PSO. This study used an equal weight of 0.5 for the scalarization of each response. Equal weightage was used because this study did not prioritize any responses and assumed that the importance of both responses is equal.Before combining two responses as one, the data must be normalized first to give a sense of fairness for each response. This normalization was conducted by rescaling the data value to between 0 and 1.

The regression model of combined objectives was built using regression in Minitab 17, after obtaining the data. This regression equation was used for optimization, using PSO. Table 6 showed the regression equation of combined objectives PLA and PGA bone screw. Afterward, PSO optimization was conducted using xlOptimizer. Several parameters needed adjustment before the optimization process. Table 7 shows the parameters used in this optimization. Figures3 and 4 show the best fitness graph of the optimization process. Table 8 shows the optimal level combination obtained after the optimization process using PSO and its predicted response values.

Table 4. P-value result of ANOVA

		P-value				
		Mold Temp. (A)	Melt Temp. (B)	Injection Time (C)	Cooling Time (D)	Packing Time (E)
PLA	Shrinkage	0.2700	0.0000	0.0330	0.3320	0.0030
	Warpage	0.1700	0.0000	0.0001	0.3880	0.0109
PGA	Shrinkage	0.0020	0.0000	0.0040	0.6300	0.3540
	Warpage	0.0000	0.0000	0.0000	0.6740	0.4190

Table 5. Regression equation

Response		Regression equation	R-sq (adj)	R-sq (pred)
PLA	Shrinkage (%)	-8.46 - 0.0154 A + 0.07667 B + 0.467 C + 0.0448 D - 0.1397 E	92.40%	89.28%
	Warpage (mm)	-0.0631 - 0.000153 A + 0.000981 B + 0.00922 C + 0.000194 D - 0.000878 E	96.35%	94.87%
PGA	Shrinkage (%)	83.3 + 0.01737 A - 0.658 B + 0.780 C + 0.0108 D - 0.0488 E + 0.001440 B*B	88.53%	83.49%
	Warpage (mm)	0.28253 + 0.000079 A + 0.000774 B + 0.006016 C + 0.000038 D + 0.000022 E	98.35%	97.37%

Table 6. Regression equation of combined objectives

Material	Regression equation	R-sq (adj)	R-sq (pred)
PLA	-2.012 - 0.00221A + 0.012562B + 0.0998C + 0.00462D - 0.01637E	95.59%	93.68%
PGA	-2.659 + 0.002210A + 0.011066B + 0.1211C + 0.00127D - 0.00403E	96.08%	94.62%

Table 7. Parameters in PSO

Parameter	Value
Number of Particle	20
Inertia Weight (ω_0)	0.8
C_1	2
C_2	2
$X_{lowerlimit}$ PLA	[10 170 1 17 10]
$X_{upperlimit}$ PLA	[38 230 3 25 20]
$X_{lowerlimit}$ PGA	[60 220 1 17 10]
$X_{upperlimit}$ PGA	[160 270 3 25 20]

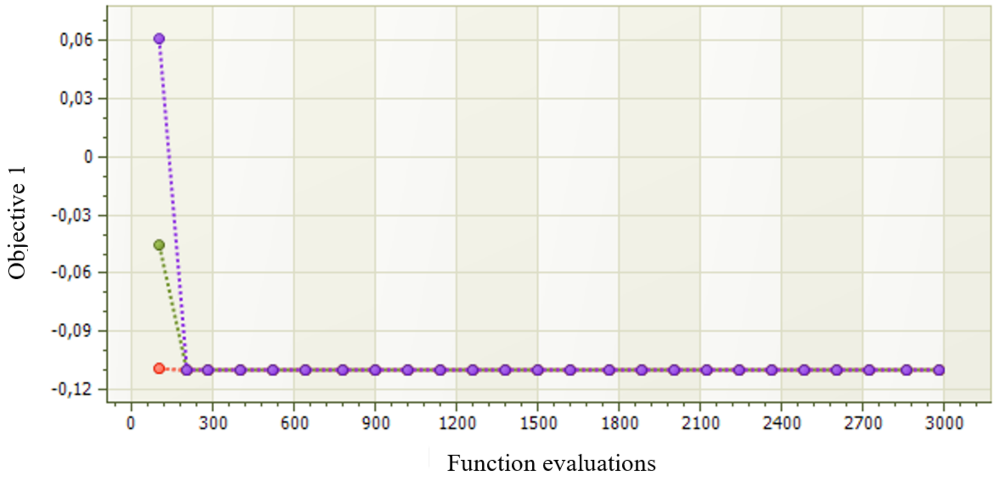

Figure 3. Best fitness graph of PLA bone screw optimization

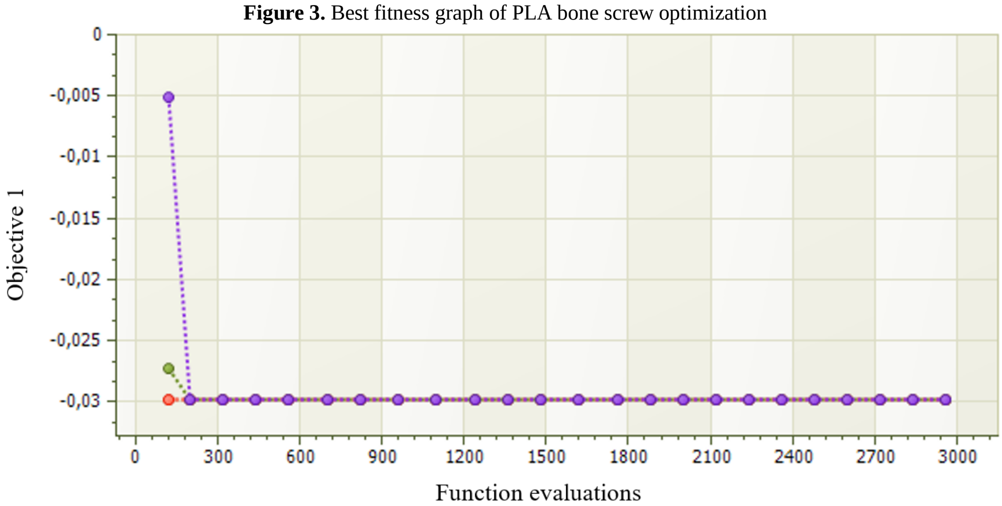

Figure 4. Best fitness graph of PGA bone screw optimization

Table 8. Optimal parameter and predicted responses

Material	A	B	C	D	E	CO	Predicted shrinkage (%)	Predicted warpage (mm)
PLA	38	170	1	17	20	-1.095	2.4233	0.0928
PGA	60	220	1	17	20	-0.0297	8.9592	0.4646

Based on the result, the optimal parameter setting for PLA bone screw includes 38°C mold temperature, 170°C melt temperature, 1 s injection time, 17 s cooling time, and 20 s packing time. For PGA bone screw, the optimal parameter setting includes 60°C mold temperature, 220°C melt temperature, 1 s injection time, 17 s cooling time, and 20 s packing time. Furthermore, PLA bone screw is preferable to PGA bone screw in terms of injection molding quality because the former had a smaller value of optimized shrinkage and warpage.The next step was study validation using experiment confirmation and mechanical simulation. Experiment confirmation was conducted by simulating the optimal parameters setting that have been previously obtained. Table 9 shows the result of experiment confirmation and its comparison to predicted values.

Based on the results shown above, the error rate of the predicted value can be measured by comparing its value with the simulated value. For PLA bone screw, the error rate of shrinkage and warpage are 6% and 10%, respectively. Conversely, the error rate for PGA bone screw shrinkage and warpage is 7% and 1%, respectively.

Mechanical simulation was performed using Autodesk Inventor to analyze von Mises stress. The von Mises stress is equivalent to the combination of three principal stresses [28]. This value was compared with the tensile strength to judge the failure of the material. Schatzker type 1 tibial plateau fracture that had been fixated using PLA and PGA bone screw was given 2560 N load on the bone. This value was determined on the basis of a total contact force of 80 kg individual's knee, in walking position [29]. Figures5 and 6 show the von Mises stress analysis results of PLA and PGA bone screws.

Table 9. Experiment confirmation results and predicted value

Material	Predicted Shrinkage (%)	Predicted Warpage (mm)	Simulated Shrinkage (%)	Simulated Warpage (mm)
PLA	2.4233	0.0928	2.278	0.0842
PGA	8.9592	0.4646	9.642	0.4612

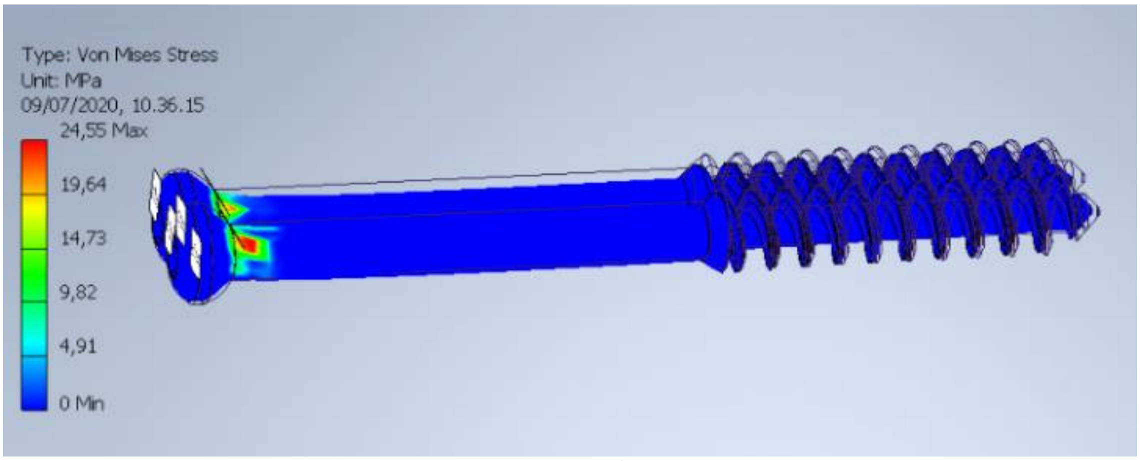

Figure 5. Von mises stress of PLA bone screw

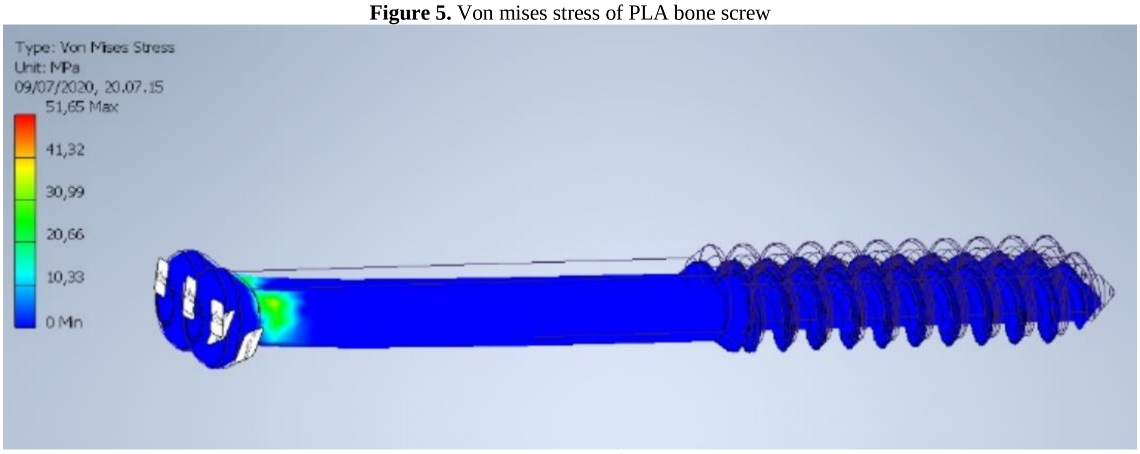

Figure 6. Von mises stress of PGA bone screw

The results show that the maximum von Mises stress of PLA and PGA bone screws was 24.55 and 51.65 MPa, respectively. These values are less than their tensile strength, which indicates that the screws can resist the load. PGA bone screw has greater von Mises stress because it has greater tensile strength too. Thus, it can be concluded that PGA bone screw had better mechanical strength than PLA bone screw.

Conclusion

This study optimized the simulation of the PLA and PGA bone screw injection molding process to minimize its shrinkage and warpage and further compared the quality of both screws. It also investigated the effect of melt temperature, mold temperature, injection time, cooling time, and packing time on shrinkage and warpage. Hence, two sets of experiments based on Taguchi orthogonal array using PLA and PGA were conducted, and the results were analyzed using ANOVA. The result of ANOVA showed that melt temperature, injection time, and packing time affected the shrinkage and warpage of PLA bone screw, whereas the parameters that have a significant effect on PGA bone screw are mold temperature, melt temperature, and injection time. The shrinkage and warpage of both screws were optimized using PSO. After the optimization process, the shrinkage and warpage value improved to 2.4233% and 0.0928 mm for PLA bone screw and 8.9592% and 0.4646 mm for PGA bone screw. Experiment confirmation shows that there were some errors between predicted and simulated values. The mechanical simulation conducted proved that both screws resisted the applied load when implemented to fixSchatzker type 1 tibial plateau fracture. Nevertheless, both screws had their own superiority toward each other. PGA bone screw had better mechanical strength than PLA bone screw based on the mechanical simulation,whereas PLA bone screw had preferable injection molding quality when compared with PGA bone screw because of its better value of shrinkage and warpage.

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