JMES The International Journal of
Mechanical Engineering and Sciences
https://iptek.its.ac.id/index.php/jmes
e-ISSN 2580-7471

Analysis of Seal Face Formation Parameters using Powder Metallurgy Technology with Taguchi Method and Gray Relational Analysis

Kurniawan[1*], Mohammad Nurdin[2], Otto Purnawarman[3], Fachrul Rozy[1]

[1]Department of Manufacturing Design Engineering, Bandung Polytechnic of Manufacturing, Kanayakan St. No.21, Indonesia
[2]Department of Foundry Engineering, Bandung Polytechnic of Manufacturing, Kanayakan St. No.21, Indonesia
[3]Department of Manufacturing Engineering, Bandung Polytechnic of Manufacturing, Kanayakan St. No.21, Indonesia

Received: 30 December 2021, Revised: 15 March 2022, Accepted: 21 March 2022

Abstract

The seal face is the main component of a mechanical seal to prevent leakage in a system with fluid flow. Seal face manufacture is generally produced by the material removal process, which causes some raw material waste. Powder metallurgy is the process of manufacturing products from metal powders with raw material efficiency of up to 97%. This study discusses the relationship between the manufacturing process parameters of seal face with SiC material through a powder metallurgy process as a substitute for manufacturing by material removal. The approach used in this research was the design of experiments with the Taguchi method and the technique of Gray Relational Analysis. Process parameters controlled were compaction pressure (*CF*), compaction time (*CH*), sintering temperature (*ST*), and sintering time (*SH*). Responses were measured in the form of surface hardness (*HV*) and density. The combination of process parameters that produces the optimum response is $CF = 408$ N/mm^2 (level 3), $CH = 2$ min (level 1), $ST = 1050°$C (level 3), $SH = 120$ min (level 2) with contribution of process parameters $CF = 38.06\%$, $CH = 2.53\%$, $ST = 49.50\%$, and $SH = 9.91\%$. The optimum surface hardness and density values were 513.03 HV and 3.04 gr/mm^3.

Keywords: Design of experiments, gray relational analysis, powder metallurgy, Taguchi method, seal face

1. Introduction

A mechanical seal is a mechanical device used to prevent leakage in a system with fluid flow [1]. Mechanical seals work by utilizing a seal face that serves as the main point of preventing leakage (primary sealing). In Indonesia, 99% of the need for mechanical seals is met from imports [2]. Domestically produced mechanical seals tend to experience damage to seal face components such as wear, sleeves, and radial looseness of the shaft. In general, seal face is made by a material removal process which causes some raw material to be wasted into scrap and cannot be utilized. Efforts to maximize usage of raw materials are conducted by research on making seal faces with powder metallurgy processes. Powder metallurgy is a product-making process from metal powders that can efficiently use raw materials up to 97% [3]. In this study, an analysis was carried out to obtain a combination of process parameters that could produce an optimum response on seal face test specimen made through the powder metallurgy process as a substitute for seal face manufacture made through the material removal process.

Powder metallurgy technology is the process of manufacturing products from metal powders. There are three main stages in manufacturing products from metal powders: the mixing process, the compacting process, and the sintering process [3]. The mixing process is mixing metal powders with a binder and lubricant from a mixture of fellow metals and non-metals. The purpose of the mixing process is to obtain a homogeneous alloy, thus facilitating the formation of the compaction process [4]. The compacting process forms metal powders by emphasizing metal powders with a compacting tool as a product mold. The sintering process is a heat treatment process given to the compacted product. The sintering process is carried out at a temperature below the melting point of the primary metal making up the powder mixture, causing the particle bonds between the powders to become strong and stiff.

1.1. Mechanical Seal

A mechanical seal is a mechanical device used to prevent fluid leakage and prevent the entry of dirt from outside into a system with a rotating shaft [5]. Mechanical seals work by utilizing two flat and smooth surfaces (seal-

*Corresponding author. Email: kurniawan@polman-bandung.ac.id.

ing faces) that rub against each other and produce a point of contact (sealing contact) due to the influence of springs and pressure from the system. The point of contact (sealing contact) is a stationary and rotary face that prevents fluid leakage. Sealing devices are classified into two types: static seals and dynamic seals. Static seals are used when little or no relative movement occurs between the surfaces in contact, whereas dynamic seals resist leakage in rotating shafts. One type of seal included in the dynamic seal is a mechanical seal. Table 1 shows the standard material used to make a seal face. Table 2 shows the consideration of the use of the main material from this research.

2. Method

2.1. Design of Experiments

The experimental research method is included in quantitative research methods. The purpose of conducting experimental research is to study the object of research to find factors that influenced the success of a research design and obtain new facts that could strengthen or reject the results of previous research [6]. The stages of experiment design can be seen in Figure 1.

The Taguchi method is a method of adapting the design of an experiment that aims to improve the quality of products and processes simultaneously, along with reducing costs and resources to a minimum. The Taguchi method makes the products or processes robust against uncontrolled factors (noise). Therefore, this method is also known as robust design. The design of the experimental approach is used to define all possible experimental conditions. The Taguchi method can provide accurate analysis with fewer trials to save time and costs.

Deng's Gray Relational Analysis technique in the 1980s can be used to optimize multiple responses simultaneously in the Taguchi method [7]. The Gray Relational Analysis technique is used in optimization to convert several responses into one response only. It can perform optimization in multi-response cases. Gray Relational Analysis is used to determine the interrelationships in several responses.

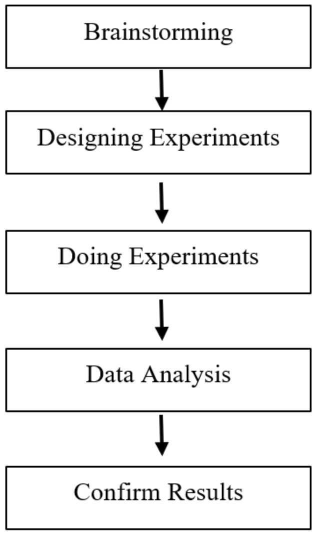

Figure 1. Stages of experimental design.

Table 1. Seal face component and materials.

No.	Parts	Materials
1	Mating Ring (Stationary Face)	Silicon Carbide (SiC), Tungsten Carbide (TC), Ceramic (Al_2O_3)
2	Primary Ring (Rotary Face)	Resin Carbon, Antimony Carbon, Silicon Carbide (SiC), Tungsten Carbide (TC)
3	O-Ring	Fluoroelastomer (Viton), NBR, Perfluroelastomer (Kalrez /Chemraz)
4	Spring	316SS, Hasteloy C, Monel, Titanium
5	Metal Hardware	316SS, Hasteloy C, Monel, Titanium

Table 2. Consideration the use of silicone carbide for the main material.

	Carbide		Carbon
	Tungsten	Silicone	
Melting point	3422°C	2730°C	4827°C
Price (IDR)	600k-900k	200k-300k	250k-400k
Availability in market	rare	normal	normal

Analysis of variance is used to see the influence of each factor on the response under study. Analysis of variance is a method for analyzing the diversity of response and dividing it into components that measure the source of variation. Then the rest is associated with the errors that occur. The source of the variation is associated with the independent variables, namely the factors being tested.

2.2. Research Method

There were five important stages in the research: planning, designing the experiment, experimenting, analyzing the experimental results, and confirming the experimental results. These stages were conducted in manufacturing seal faces with powder metallurgy technology using the Taguchi method and Gray Relational Analysis techniques [8].

The response was a reaction caused by a change in the value of a factor. In this study, the response was selected based on the material properties of the seal face product. The selected responses had an image of desired final properties of the seal face. The responses chosen for the seal face were surface hardness (*HV*) and density. The factor was anything in an experiment that affected the value of a response. In this study, the factors were selected using a fishbone diagram approach which can be seen in Figure 2. Table 3 shows the variables and levels of factors controlled to produce the optimum response.

In this study, the full factorial method was not used. The full factorial method allowed estimation of main effects and interactions but required more samples and time. The orthogonal matrix obtained for this study based on Table 4 was $L_9(3^4)$. The number of experiments carried out was 9, the number of degrees of freedom of the orthogonal matrix was 8, and the matrix used for the number of factors was 4, with each factor having a variation of 3 levels. An experimental design with the Taguchi method was obtained using the Minitab software, as shown in Table 4.

Several machines and tools were used in the process of making seal face with powder metallurgy, including:

1. The mixing process used a powder mixer machine.
2. The compaction process used a hydraulic press machine.
3. The sintering process used an annealing furnace.
4. Powder mold used a compacting tool.

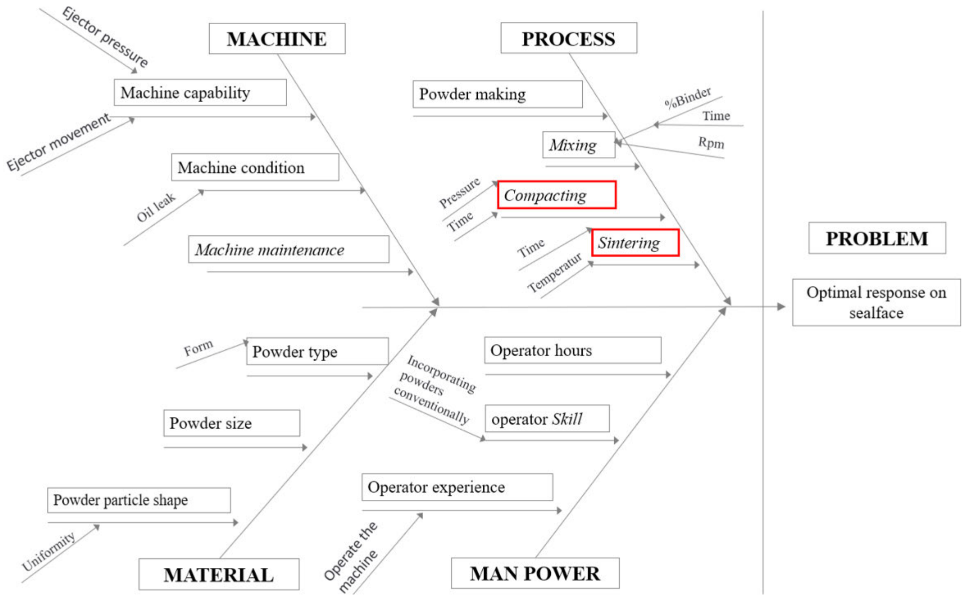

Figure 2. Fishbone diagram.

Table 3. Defined variables and levels of factors.

	Variable	Level of Factor 1	Level of Factor 2	Level of Factor 3
A	Compaction pressure (*CF*)	289 N/mm^2	342 N/mm^2	394 N/mm^2
B	Compaction time (*CH*)	2 min	3 min	4 min
C	Sintering temperature (*ST*)	900°C	975°C	1050°C
D	Sintering time (*SH*)	60 min	120 min	180 min

Table 4. Experimental design using the Taguchi method.

No	Variable			
	CF (N/mm^2)	*CH* (min)	*ST* (°C)	*SH* (min)
1	289	2	900	60
2	289	3	975	120
3	289	4	1050	180
4	342	2	975	180
5	342	3	1050	60
6	342	4	900	120
7	408	2	1050	120
8	408	3	900	180
9	408	4	975	60

The SiC metal powder alloy's composition was made based on the literature [9] with the percentage of material as shown in Table 5. Table 6 shows that the binder composition that produced the highest strength value was found in the binder composition bounded by the red line with 0.1% lubricant. Thus the binder composition used in this study is shown in Table 7.

The research process was carried out from mixing, compacting, sintering, and testing the surface hardness and density, as shown in Figure 3. Each stage of the process was carried out based on predetermined variables and levels of factors. After the seal face was produced, the response data retrieval process was carried out with three replications. Replication was done to minimize noise on the data obtained.

Table 5. Percentage of material to be processed.

Parts	Materials
Main material of the seal face	Silicone carbide Powder (SiC)
Binder (20% of the total weight of the main material)	Hydrogenated caster oil Oleic Acid Liquid paraffin Vasseline petroleum
Lubricant (0,1% of the total weight of the main material)	Zinc Stearate

Table 6. Binder composition on the properties of the product.

Properties	Synthesis Route	Binder Composition, wt %		
		Paraffin - 8.5 Castor Oil - 0.6 Oleic Acid - 5.0 Petroleum - 8.59	PVA - 5.0 Citric Acid - 0.5 Urea - 4.0 Water - 90.5	Phenolformaldehyde Resin -100
Tensile strength of the sintered rings, MPA	SHS	135	132	123
	Acheson	108	104	97
Density of the sintered rings, kg/m^3	SHS	3184	3180	3085
	Acheson	3118	3107	3004

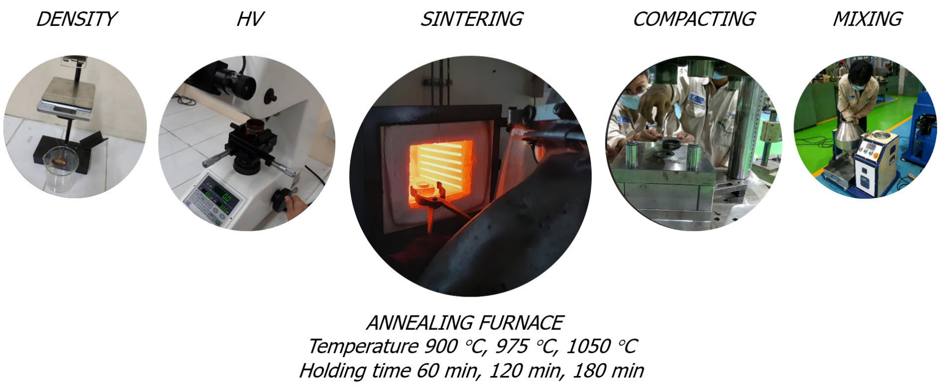

Figure 3. Seal face research process.

2.3. Data Analysis

In Table 8, the smallest hardness value of the test specimen was found in experiment no. 1 with a value of 106.580 HV, and the highest hardness value was found in experiment no. 7 with a value of 513.032 HV. While the lowest density value was found in experiment no. 1 with a value of 2,364 gr/mm^3, and the Highest value of density measurement is in experiment no. 7 with a value of 3,038 gr/mm^3. The results of the calculation of the S/N ratio of each response are shown in Table 9. A combination of control factors could be taken from the GRG main effect to produce optimum response values, as shown in Table 10.

In Figure 4, the value of compaction pressure (*CF*) and sintering temperature (*ST*) had a linear graph. If compaction pressure (*CF*) and sintering temperature (*ST*) values were increased, the resulting response would be more optimal. The graph of compaction time (*CH*) had an optimum value at the first level (2 min). If the compaction time (*CH*) were set at the first level (2 min), it would produce an optimum response. The graph of sintering time (*SH*) had an optimum value at the second level (120 min). If the sintering time (*SH*) were set to the second level (120 min), it would produce an optimum response.

Table 7. Percentage of binder composition.

Binder	Percentage
Hydrogenated caster oil	8%
Oleic Acid	1%
Liquid paraffin	10%
Vasseline petroleum	81%

Table 8. Variables and responses from trial combinations.

No	Variable				X	
	CF	*CH*	*ST*	*SH*	*HV*	ρ
1	289	2	900	60	106.580	2.364
2	289	3	975	120	343.100	2.540
3	289	4	1050	180	356.503	2.750
4	342	2	975	180	254.700	2.538
5	342	3	1050	60	315.372	2.745
6	342	4	900	120	251.763	2.416
7	408	2	1050	120	513.032	3.038
8	408	3	900	180	215.930	2.676
9	408	4	975	60	460.031	2.767

Table 9. Gray relational analysis data processing.

No	Parameters				S/N Ratio Normalisation		ΔHV	Δr	*GC HV*	*GC r*	*Gi*	Rank
	CF	*CH*	*ST*	*SH*	*HV*	*P*						
1	289	2	900	60	0.000	0.000	1.000	1.000	0.333	0.333	0.333	9
2	289	3	975	120	0.744	0.285	0.256	0.715	0.661	0.412	0,536	5
3	289	4	1050	180	0.767	0.608	0.233	0.392	0.682	0.561	0,621	3
4	342	2	975	180	0.554	0.281	0.446	0.719	0.529	0.410	0,469	7
5	342	3	1050	60	0.690	0.600	0.310	0.400	0.618	0.556	0,587	4
6	342	4	900	120	0.546	0.087	0.454	0.913	0.524	0.354	0,439	8
7	408	2	1050	120	1.000	1.000	0.000	0.000	1.000	1.000	1.000	1
8	408	3	900	180	0.449	0.496	0.551	0.504	0.476	0.498	0,487	6
9	408	4	975	60	0.931	0.632	0.069	0.368	0.878	0.576	0,727	2
						Max	1.000	1.000		Min	0.333	
						Min	0.000	0.000		Max	1	

Table 10. Optimum response table based on the main effect of the mean GRG.

Variable	Rank	Level
Compaction pressure (*CF*)	2	level 3
Compaction time (*CH*)	4	level 1
Sintering temperature (*ST*)	1	level 3
Sintering time (*SH*)	3	level 2

Figure 4. Main effect graph of mean GRG.

Table 11. Analysis of variance from GRG.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-value	P-Value
CF	2	0.115	38.06%	0.115	0.058	*	*
CH	2	0.008	2.53%	0.008	0.004	*	*
ST	2	0.150	49.50%	0.150	0.075	*	*
SH	2	0.030	9.91%	0.030	0.015	*	*
Error	0	*	*	*	*		
Total	8	0.303	100.00%				

Table 12. Analysis of variance after pooling.

Source	DF	Seq SS	Contribution	Adj MS	F-value	Pure SS
CF	2	0.115	35.53%	0.057	15.063	0.108
CH	2	0.008	-	-	-	-
ST	2	0.150	46.98%	0.075	19.592	0.143
SH	2	0.030	7.38%	0.015	3.922	0.022
Error	2	0.008	10.11%	0.030		
Total	8	0.303	100.00%			

The results of the ANOVA calculation are shown in Table 11. Pooling up was one of several steps to achieve the ANOVA result if the degree of freedom error was zero [6]. With pooling up, factors combined with the value of the sum of the small squares and a small percentage of contribution (factors that do not have a significant effect) with the square of error. Pooling up was done to get the F-Value [10]. In the Taguchi method, the process of combining factors with the value of the sum of small squares and a small percentage of contribution is carried out until the error-free degree was close to half of the total degrees of freedom of observation and the data already had an F-value that was greater than the F-table value. In this case, pooling was carried out on the compaction time factor (*CH*) because it had the smallest contribution with 2.53%. ANOVA result after pooling are shown in Table 12.

The hypothesis used in this study:

1. H_0: The factor does not have a significant effect on the response value, so $\mu_1 = \mu_2 = \ldots = \mu_j = \mu_k$
2. H_1: Factors have a significant influence on the response value.
3. F-table $F_{.10}$ (2;6) 90% confidence is 3.4633.

Each factor had a relationship in influencing the optimum response. The interactions between factors that produced an optimum response to the GRG value based on Figure 5 were:

1. The compaction pressure was set at the third level (408 N/mm^2), and the compaction time was set at the first level (2 min).
2. The compaction pressure was set at the third level (408 N/mm^2), and the sintering temperature was set at the third level (1050°C).
3. The compaction pressure was set at the third level (408 N/mm^2), and the sintering time value was at the second level (180 min).
4. The compaction time was set at the first level (2 min), and the sintering temperature was set at the third level (1050°C)
5. The compaction time was set at the first level (2 min), and the sintering time was set at the second level of hold (120 min).
6. The sintering temperature was set at the third level (1050°C), and the sintering time was set at the second level (120 min).

2.4. Confirmation and Validation of Data Analysis

The optimum condition prediction (μ_{pred}) of GRG is calculated based on the combination of the main effect value of the process parameters that produce the optimum response with $\overline{X}$ is the average of the data. Optimum condition prediction (μ_{pred}) can be calculated by the following equation:

$$\mu_{pred} = \overline{X} + (\overline{CF}_3\text{-}\overline{X}) + (\overline{CH}_1\text{-}\overline{X}) + (\overline{ST}_3\text{-}\overline{X}) + (\overline{SH}_2\text{-}\overline{X})$$

GRG prediction value:

$$\mu_{pred} = 0.578 + (0.738\text{-}0.578) + (0.601\text{-}0.578) + (0.736\text{-}0.578) + (0.658\text{-}0.578)$$
$$\mu_{pred} = 0.9998$$

2.4.1. Confidence interval

The calculation of the average confidence interval for the predicted GRG optimization results is as follows:

$$CI_p = \sqrt{\frac{F_{(\alpha,df_F,df_E)} MS_E}{n_{eff}}}$$
$$F_{(\alpha,df_F,df_E)} = F_{(0.1,2,2)} = 9.000$$
$$MS_E = 0.0038$$
$$n_{eff} = 9$$
$$CI_p = \sqrt{\frac{9{,}000 \times 0{,}0038}{9}}$$
$$CI_p = \pm\, 0.061644$$

Thus, the confidence interval for the predicted GRG average value that produces the optimum response with a 90% confidence level is 0,9998 $\pm$ 0.0616 or (0,9382 < $\hat{\mu}$GRG < 1,000).

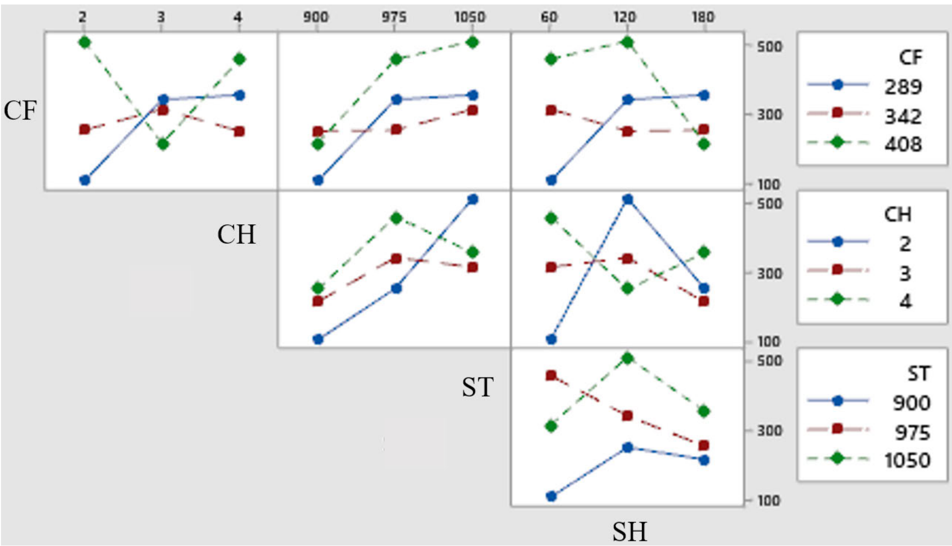

Figure 5. Interaction between factors in influencing the value of multi-response.

Table 13 shows the optimum response value from the confirmation experiment. The results of the confirmation experiment GRG calculation was as follows:

$$\mu_{confirm} = 0.581 + (0.742\text{-}0.581) + (0.602\text{-}0.581) + (0.741\text{-}0.581) + (0.659\text{-}0.581)$$
$$\mu_{confirm} = 0.9999$$

3. Result and Discussion

Figure 6 shown the difference in the percentage of binder used in the alloy will produce a seal face with different characteristics. In this study, a binder with a percentage of 20% was chosen because it can produce a seal face that is not prone to damage during compaction processing and can reduce the powder that enters the mold.

Figure 7 shown the difference in holding time and the temperature rise every minute will result in a different final shape of the seal face [3]. The reaction in the alloy was not able to compensate for the increase in temperature every minute. A certain holding time is required for each temperature increase to ensure the seal face gets the desired final result [5].

From the results of the research that has been carried out, the manufacture of seal face test specimens from powder metallurgy technology using the Taguchi method and the Gray Relational Analysis technique, a combination of process parameters (control factors) that produced an optimum response value (highest hardness 514.17 HV and highest density 3,00 gr/mm^3) can be seen in Table 14.

This study was designed by estimating the factors that might influence the response. All control factors are determined to see the how each factor influence on the response. After getting the factors that affect the response significantly, a combination is made to produce the optimum response. All control factors (except the control factors that were pooled) resulted in the H_1 hypothesis based on the F test table which can be seen in Table 15.

Table 13. Confirmation experiment response table.

Factor	Level			Response		
	1	2	3			
Compaction pressure (*CF*)	289	342	**408**	Hardness (*HV*)		
Compaction time (*CH*)	**2**	3	4	515.5	514.2	512.7
Sintering temperature (*ST*)	900	975	**1050**	Density(ρ)		
Sintering time (*SH*)	60	**120**	180	2.96	3.02	2.98

(a) **10% BINDER** (b) **20% BINDER** (c) **30% BINDER**

Figure 6. Seal face produced from binders with different percentages.

Table 14. Parameters of the process of making seal face test specimens.

Factor	Rank	Level
Compaction pressure (*CF*)	2	level 3
Compaction time (*CH*)	4	level 1
Sintering temperature (*ST*)	1	level 3
Sintering time (*SH*)	3	level 2

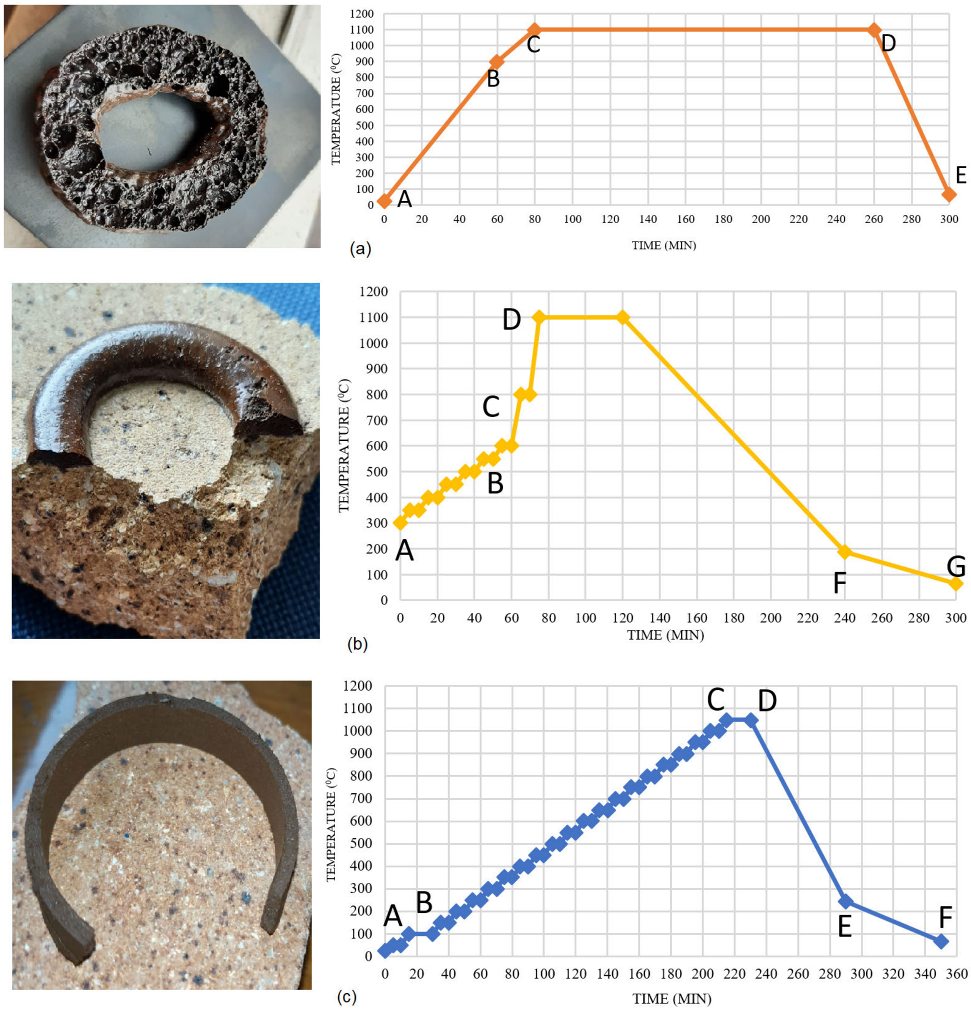

Figure 7. The difference in holding time with temperature results in different seal face (a) Experiment 1, (b) Experiment 2, (c) Experiment 3.

Table 15. F test for GRG.

Hypothesis	Factor	F test	Contribution
H1	Compaction pressure (*CF*)	15.06 >3.46	35.53%
-	Compaction time (*CH*)	POOLING	-
H1	Sintering temperature (*ST*)	19.59 >3.46	46.98%
H1	Sintering time (*SH*)	3.92 >3.46	7.38%
	Error		10.1 %

The compaction pressure (*CF*), sintering temperature (*ST*), and sintering time (*SH*) factor significantly influenced the hardness value and density value of the seal face test specimen. The sintering temperature (*ST*) and compaction pressure (*CF*) had the largest percentage contribution to the response, 46.98% and 35.53%, respectively.

The hardness of the carbide seal face on the material properties of the centrifugal pump [4] has a value of 86-88 HRC and density 3,00 gr/mm^3. From the experiments that have been done, highest hardness was 514.17 HV (50 HRC) and highest density was 3,00 gr/mm^3.

Figure 8 are shown the seal face dimensions (dimension in 45 mm, dimension out 50 mm shown in Figure 8). After measuring the seal face produced by powder metallurgy, based on respective combinations, it was known that there are differences in the accuracy of the product dimensions. The accuracy and precision of the seal face produced by powder metallurgy still had to be developed to meet the required dimensions with little or no machining process. The dimension for the highest and lowest respon are shown in Table 16 and Table 17.

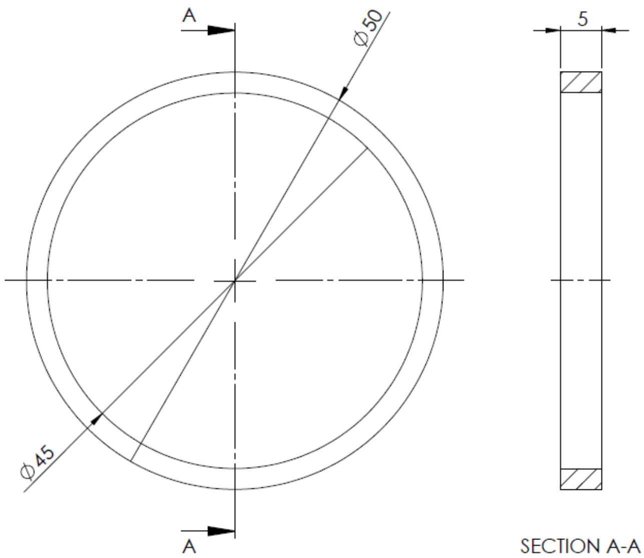

Figure 8. Seal face dimensions.

Table 16. Dimension control for the lowest respon parameters combination.

11 / 1050 3	Upper part (mm)		Lower part (mm)	
No	in	out	in	out
1	42.20	47.50	43.70	49.00
2	42.70	47.52	43.80	48.80
3	42.16	47.50	43.60	48.90
X	**42.35**	**47.51**	**43.70**	**48.90**
	1.35	1.39		
0,05	5.15		5.20	

- The difference between the average upper (in) dimension and the average lower (in) dimension:

43.70 – 42.35 = 1.35

- The difference between the average upper (out) dimension and the average lower (out) dimension:

48.90 – 47.51 = 1.39

- The difference between the average upper (out) dimension and the average lower (in) dimension:

47.51 – 42.35 = 5.35

- The difference between the average lower (out) dimension and the average lower (in) dimension:

48.90 – 43.70 = 5.20

Table 17. Dimension control for the highest respon parameters combination.

15,5 / 1050 2	Upper part (mm)		Lower part (mm)	
No	in	out	in	out
1	42.90	47.90	43.10	48.70
2	43.00	48.00	42.80	49.00
3	43.30	48.20	43.30	48.80
X	**43.07**	**48.03**	**43.07**	**48.83**
	0.00	0.80		
0,80	4.97		5.76	

- The difference between the average upper (in) dimension and the average lower (in) dimension:

43.07 – 43.07 = 0.00

- The difference between the average upper (out) dimension and the average lower (out) dimension:

48.83 – 47.03 = 0.80

- The difference between the average upper (out) dimension and the average lower (in) dimension:

48.03 – 43.07 = 4.96

- The difference between the average lower (out) dimension and the average lower (in) dimension:

48.83 – 43.07 = 5.76

4. Conclusion

This research aims to produce a seal face with good quality from the powder metallurgical process to reduce material waste from the conventional seal face manufacturing process. Good quality certainly requires factors that need to be controlled. This research is expected to be able to develop the manufacture of the seal face through powder metallurgy. Seal face from powder metallurgy has better quality than material removal to save material waste.

References

[1] R. K. Roy, *Design of Experiments Using The Taguchi Approach*. New York: John Wiley & Sons, 2001.

[2] I. Soejanto, "Desain eksperimen dengan metode Taguchi," *Yogyakarta: Graha Ilmu*, 2009.

[3] J. Li, X. Ren, Y. Zhang, and H. Hou, "Silicon carbide hot pressing sintered by magnesium additive: Microstructure and sintering mechanism," *Journal of Materials Research and Technology*, vol. 9, no. 1, pp. 520–529, 2020.

[4] K. Torosyan and V. Pak, "Influence of the binder composition on the properties of the silicon carbide green compacts and sintered parts prepared from the powders produced by SHS," in *IOP Conference Series: Materials Science and Engineering*, vol. 558, p. 012052, IOP Publishing, 2019.

[5] W. K. You, J. P. Choi, S. M. Yoon, and J. S. Lee, "Low temperature powder injection molding of iron micro-nano powder mixture," *Powder technology*, vol. 228, pp. 199–205, 2012.

[6] S. Yuwono and E. Mulyono, "Kajian pemakaian gland packing pengganti mechanical seal pompa kondensor," *Hasil hasil Penelitian EBN*, p. 420, 2009.

[7] Kurniawan and O. Yudianto, "Kajian kegagalan kinerja sil mekanik produksi dalam negeri," *Seminar Nasional - XIII Rekayasa dan Aplikasi Teknik Mesin di Industri, Bandung*, Nov. 2014.

[8] M. P. Groover, *Fundamentals of Modern Manufacturing*. Pennsylvania: John Wiley & Sons, 2010.

[9] H. Manalu, "Studi kasus audit maintenance rotating equipment," p. 46, Medan: Departemen Teknik Mesin Fakultas Teknik Universitas Sumatera Utara, 2012.

[10] C. Lin, J. Lin, and T. Ko, "Optimisation of the EDM process based on the orthogonal array with fuzzy logic and grey relational analysis method," *The International Journal of Advanced Manufacturing Technology*, vol. 19, no. 4, pp. 271–277, 2002.