Optimization of Stir Casting Process Parameters to Minimize the Specific Wear of Al-SiC Composites by Taguchi Method

Sadi [#1], Viktor Malau[#2], M Waziz Wildan [#3], Suyitno[#4]
[#] Mechanical and Industrial Engineering Department, Gadjah Mada University
Jl. Grafika no.2, Yogyakarta, 55281, Indonesia
[1] sadi.sadi1971@yahoo.co.id
[2] malau@ugm.ac.id
[3] m_wildan@ugm.ac.id
[4] suyitno@ugm.ac.id

Abstract— The aim of this research is to optimize of stir casting process parameters to minimize the specific wear of Al-SiC composites by Taguchi method. Composite material used in this research was Al-Si aluminum alloy as the matrix and SiC (silicon carbide) particles size 400 mesh as the reinforcement. Experimental design used L_{16} orthogonal arrays Taguchi method standards. Experimental factors used in the making of composite samples were SiC content, melt temperature, rotation speed and stirring duration, each with 4 levels or variations. The microstructures of Al-SiC composite were observed by scanning electron microscope (SEM). Experimental result showed that the optimum of stir casting process parameters are SiC content of 15 wt.%, melt temperature of 740 ^{o}C, rotation speed of 300 rpm and stirring duration of 10 minutes. The most significant parameter which affected on specific wear was SiC content which contributes 88.67%. Adding content of SiC from 0 to 15 wt. % can decrease the specific wear of Al-SiC composites about 90.08 %.

Keyword- Al-SiC composites, specific wear, Taguchi method, experimental design, stir casting

I. INTRODUCTION

Optimization of the materials and processes for obtaining metal matrix composites (MMC) usable in industry is a very important thing to do. When the metal matrix was reinforced with high strength materials, the composite may be very brittle and the reinforcement can have thermal dynamic incompatibility with many metals used as matrix [1]. The MMC can be utilized at high temperature condition, furthermore the reinforcements can improve specific stiffness, specific strength, abrasion resistance, creep resistance, thermal conductivity and dimensional stability. Several advantages of MMC compared with the polymer matrix composites were higher operating temperatures and greater resistance to degradation by organic fluids [2].

MMC application on the automotive industry was used as the material of cylinder liners of engine, connecting rod, brake rotors, brake drums, etc [3]. Al-SiC MMC were made by stir casting process, which are melting and stirring process in the furnace, continued with pouring process in metal mould using gravity force. Chawla et al [3] stated that stir casting process is less expensive than the making process of other Al-SiC MMC and can also be used to make more complex components. Stirring in semi-solid conditions can break aluminum dendrite structures when they solidified to be a form of small equiaxed structure or chill-type [4].

Naher et al [5] and Bhushan et al [6] stated that stirring can be used to increase SiC particles distribution on aluminum matrix. Less homogenous distribution of SiC particles on the matrix caused the mechanical properties of Al-SiC MMC become inferior compared with homogenous distributed. To obtain homogenous distribution, optimum stirring speed on Al7075/SiC composites with SiC 10 % in weight is 650 rpm, above those will cause high porosity. Aqida et al [7] and Ravi et al [8] stated that porosity is a defect with smooth holes formed by gas trapped during mixing process with stirring and shrinkage during the solidification process. Porosity is also formed by interfacial reaction, oxygen and hydrogen causing appearance of water steam on the SiC particles surface. The bigger grain size of SiC particles, will make high composites porosity [9].

In order to improve Al-SiC MMC wear resistance with stir casting process, besides analyzing SiC distribution, other stir casting process factor such as the number of SiC weight fraction, stirring speed, stirring time, temperature of melt, etc also conducted. Ramachandra et al [10], Basavarajavva et al [11], Hasan et al [12] and Purohit et al [13] in their analysis concluded that Al-SiC composites wear resistance was improved with the increasing of SiC particles content on the aluminum matrix. In the same testing, increasing in wear test load will increase the wear rate [14]. On dry sliding wear behavior, content of SiC particles 10 weight % on Al-SiC MMC will reduce wear rate of 15-25% [12]. Singla et al [15], Rajeev et al [16] and Mishra et al. [17], their results showed that wear rate increased with increasing of normal load, while mean of friction coefficient decrease with increasing of load. Basavarajavva et al [11], Rao et al [14] and Kumar et al [18] in their analysis also showed that increasing sliding distance will decreasing of Al-SiC composites wear, but increasing sliding time and time of testing will increasing of composites wear loss ([19], [20]). Increasing of sliding speed will decreasing of composites wear rate and friction coefficient [21].

The aim of this research is to optimize of stir casting process parameters to minimize the specific wear of Al-SiC composites by Taguchi method. This research also aimed to analyze the effect of stir casting process parameters (SiC content, melt temperature, rotation speed and duration of stiring) changes on specific wear of Al-SiC composites.

II. EXPERIMENTAL PROCEDURE

Experimental procedures in this research are materials test, stir casting process of Al-SiC composites, wear test and microstructure observation with presented below:

A. Materials

In this research, Al-Si aluminum alloy ingot was cut into scrap. The Al-Si aluminum alloy scrap was used as the composites matrix materials and SiC particles grain sized 400 mesh (32 μm) used as the reinforcement materials. Chemical compositions of the Al-Si aluminium alloy ingot in weight % were 10.516 Si, 1.715 Cu, 0.78 Fe, 0.83 Zn, 0.239 Mg, 0.15 Mn and balance Al. Morphology of SiC particle forms were angular. Chemical compositions of SiC particles in weight % used in this research were quantitatively analyzed by energy dispersive spectroscope (EDS), the results were 21.87 % C and 78.13 % Si. The Al-Si aluminum alloy materials were supplied by Pinjaya Logam, Co., Indonesia and the SiC particles were supplied by Sigma Aldrich, Co., USA. The SiC particles forms was observed with scanning electron microscope (SEM), can be seen in Fig. 1**.**

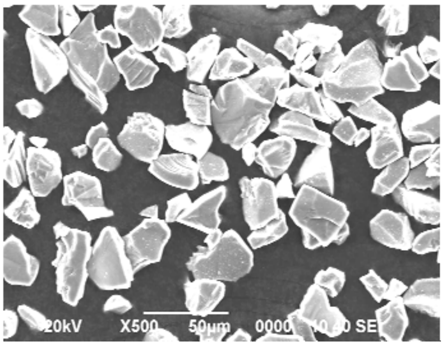


Fig. 1. SEM micrograph of SiC particles

B. Stir Casting Process of Al-SiC Composites

The Al-Si aluminum alloy scrap were heated up in the graphite crucibles in a resistance furnace until the above melting point (above 680 ^{o}C) to make sure that the Al-Si aluminum alloy perfectly melted, before it mixed with SiC particles. The Al-Si aluminum alloy scrap were pre-heated at temperature of 500 ^{o}C and holding time of 2 hours. At the same time, SiC particles were also pre-heated at temperature of 500 ^{o}C for 2 hours before they mixed with Al-Si aluminum alloy liquid to eliminate the water vapor on its surface. The melted Al-Si aluminum alloy was mixed with SiC particles by stirring process. The stirring was conducted to obtain evenly distribution of SiC particles on aluminum matrix. Stirring process was conducted in two steps, which were stirring in a slurry condition (on temperature 580 ^{o}C) for 30 minutes with rotation speed 600 rpm and stirring on melted condition according to process parameters using in the experimental design. On this step, argon gas was flown into graphite crucibles to push the oxygen out of the composite melted surface. Process parameters and factors used in this experiment were SiC content (0, 5, 10, 15 wt.%), melt temperature (680, 700, 720, 740 ^{o}C), rotation speed (100, 200, 300, 400 rpm) and stirring duration (10, 20, 30, 40 minutes). The Al-SiC composites liquid then poured into the steel mould which pre-heated at temperature of 200 ^{o}C. The Al-SiC composites formed in the mould were solidified and cooled for 2 hours, before taken out from the mould.

C. Wear Test

Wear test was investigated by abrasion wear test machine Ogoshi OAT-U to observe spesific wear. In this test, specimen weared abrasively with rolling steel disc. Specimen dimension for wear testing was 50 mm length, 30 mm width and 5 mm thickness. Wear testing used normal load parameters i.e P = 2.12 Kg, speed V = 0.244 m/second, wear time of 5 second and sliding distance Lo = 1.22 m. Dimension for rolling wearing disc was r = 13.5 mm and thickness B = 1.497 mm. Spesific wear value can be determined using the following equation 1 [22] .

$$W_s = \frac{1.5\, W_o}{P_o L_o} \tag{1}$$

where W_s, Wo, P_o dan L_o are specific wear (mm^3/kg.m), wear material volume (mm^3), normal load (kg) and sliding distance (m) respectively. The schematic diagram of specimen wear test process on Ogoshi test machine was shown in Fig. 2**.**

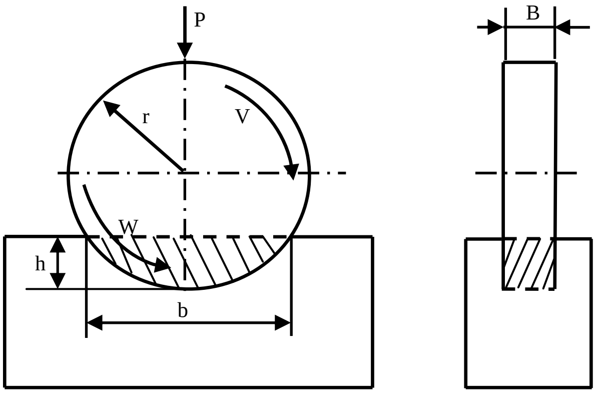


Fig. 2. Schematic diagram of wear test [22]

Where P is a load, h is abrasion depth, b is abrasion width, r is radius of disc, W is amount abraded, V is abrasion speed and B is thickness of disc.

D. Microstructure Observation

In this research, microstructure observation were conducted by polishing the specimen surface. Polishing the specimen was done by using silicon carbide abrasive paper sized of 400, 600, 800, 1000, 1200 and 1500 grade. After polished with abrasive paper, specimens were scrubbed with smooth fabric and autosol to obtain smooth surface and no scratch. Smoothed specimen was then etched by dipping it into alcohol 95 %. Then the microstructure of Al-SiC composites casting specimen was observed by scaning electron microscope (SEM) to observe wear surface of wear disc former scratch on Al-SiC composites specimen.

E. Taguchi Experimental Design

Taguchi Experimental design was used in this research and 4 number of experimental factors with 4 levels or variation each, and total degree of freedom 12. Based on the number of controlled factors, number of levels and number of degree of freedom, experimental design standard according to Taguchi method was L_{16} orthogonal array, which means the number of experiment with different treatment should be conducted minimum 16 times. This research aims to obtain minimum specific wear, based on Taguchi method signal to noise ratios (S/N ratio) value obtained using response characteristics of smaller is better. To obtain S/N ratio, specific wear result test data for each experiment converted using equation 2 [23].

$$S/N\ ratio = -10 \log_{10} [\sigma^2 + Y^2] \quad (2)$$

where S/N ratio, σ dan Y are signal to noise ratio (dB), standard deviation and mean of wear test samples (mm^3/kg.m). Stir casting was conducted on 16 experiments to make Al-SiC composites specific wear test specimen. Casting for every experiment used 120 grams Al-Si alloy materials and repeated 3 times and 2 specimen was taken for each repetition, so the number of testing specimen for every experiment was 6. Total number of specific wear test specimen for 16 experiments was 96. Results on every experiment of specific wear testing were then averaged and converted into S/N ratio–smaller is better (dB) data.

III. EXPERIMENTAL RESULT AND DISCUSSION

Experiment condition and average result of specific wear test for each experiment based on L_{16} orthogonal array is shown in Table I. Response data of experiment results were calculated by MINITAB 16 and Excel software to rank factor order affecting specific wear. Result of response specific wear (average) and S/N ratio of this research are shown in Table II and Table III. Based on Table II and Table III, the rank order factors affecting specific wear (mean) and S/N ratio Al-SiC composites are SiC content, melt temperature, stirring duration and rotation speed.

TABLE I
Design of Experiment Using L_{16} Orthogonal Array and Their Results

Exp.	Experimental Factors and Process Parameters				Specific Wear Average (mm^3/kg.m)	S/N Ratios (dB)
	SiC Content (wt. %)	Melt Temperature (^oC)	Rotation Speed (rpm)	Stirring Duration (minute)		
1	0	680	100	10	0.0249	31.3049
2	0	700	200	20	0.0266	30.0397
3	0	720	300	30	0.0268	31.1933
4	0	740	400	40	0.0185	34.3979
5	5	680	200	30	0.0183	34.1832
6	5	700	100	40	0.0224	32.9123
7	5	720	400	10	0.0149	36.3936
8	5	740	300	20	0.0145	35.9764
9	10	680	300	40	0.0033	49.1275
10	10	700	400	30	0.0109	39.1558
11	10	720	100	20	0.0052	44.0066
12	10	740	200	10	0.0011	57.3794
13	15	680	400	20	0.0032	47.7452
14	15	700	300	10	0.0019	53.8265
15	15	720	200	40	0.0031	49.4208
16	15	740	100	30	0.0014	56.0730

TABLE II
Response Table for Mean of Specific Wear

Factors	Variation and Mean of Specific Wear (mm^3/kg.m)				Delta	Rank
	1	2	3	4		
SiC content (wt. %)	0.0242	0.0175	0.0051	0.0024	0.0218	1
Melt temperature (^oC)	0.0124	0.0154	0.0125	0.0089	0.0066	2
Rotation speed (rpm)	0.0135	0.0122	0.0116	0.0118	0.0019	4
Stirring duration (minute)	0.0107	0.0124	0.0143	0.0118	0.0037	3

TABLE III
Response Table for Mean of S/N Ratios – Smaller is Better

Factors	Variation and Mean of S/N Ratios – Smaller is Better (dB)				Delta	Rank
	1	2	3	4		
SiC content (wt. %)	31.74	34.87	47.42	51.77	20.03	1
Melt temperature (^oC)	40.59	38.98	40.25	45.96	6.97	2
Rotation speed (rpm)	41.08	42.53	42.76	39.42	3.33	4
Stirring duration (minute)	44.73	39.44	40.15	41.46	5.29	3

A. Effect of Various Process Parameters on Specific wear and S/N ratio-smaller is better.

SiC content variation used in this research were 0, 5, 10, 15 wt. %, melt temperature of 680, 700, 720, 740 ^oC, rotation speed of 100, 200, 300, 400 rpm, and stirring duration of 10, 20, 30, 40 minutes. Calculation result for specific wear response data (mean) and S/N ratio of each experiment (in Table II and Table III) were plotted based on factor parameters of variation/level. The effect of factors on mean of specific wear (mm^3/kg.m) and S/N ratio (dB) are shown in Fig. 3 (a-d) and Fig. 4 (a-d)**.**

Plotting results show clearly that increasing SiC content from 0 to 15 wt. % make the specific wear (means) decreases from 0.0242 to 0.0024 mm^3/kg.m. The highest S/N ratio is on the fourth variation which is 51.77 dB on content of SiC 15 wt.%, so the optimum specific wear obtained on the condition content of SiC 15 wt. %. The composite specific wear was decreased because adding SiC particles content can increase the sum of SiC particles spreading on the aluminum matrix. Increasing of SiC particles content on aluminum matrix made the composite hardness increase ([24], [25], [26], [27], [28], [29]). The increase of composite hardness made the specific wear decrease. Result of this study (in Fig. 3.a) was consistent with the studies conducted by Ramachandra et al [10], Basavarajavva et al [11], Hasan et al [12] , Purohit et al [13] and Pradeep [30], the results show the same phenomenon, that increasing SiC particles content on metal matrix can decrease the wear rate of composite.

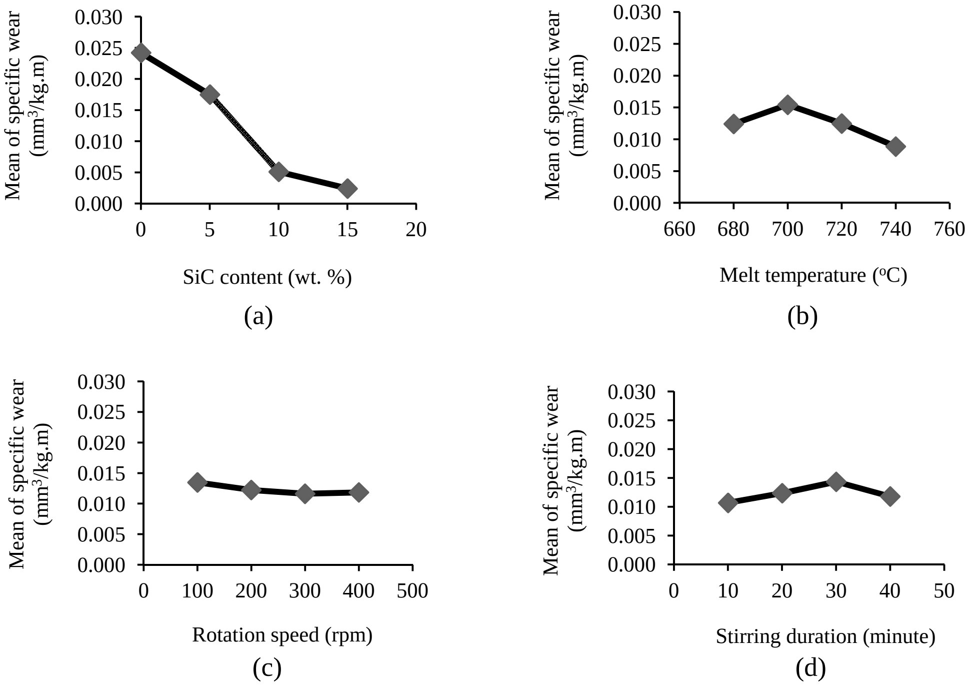


Fig. 3. The effect of process parameters on mean of specific wear (a) The effect of SiC content on mean of specific wear (b) The effect of melt temperature on mean of specific wear (c) The effect of rotation speed on mean of specific wear (d) The effect of stirring duration on mean of specific wear

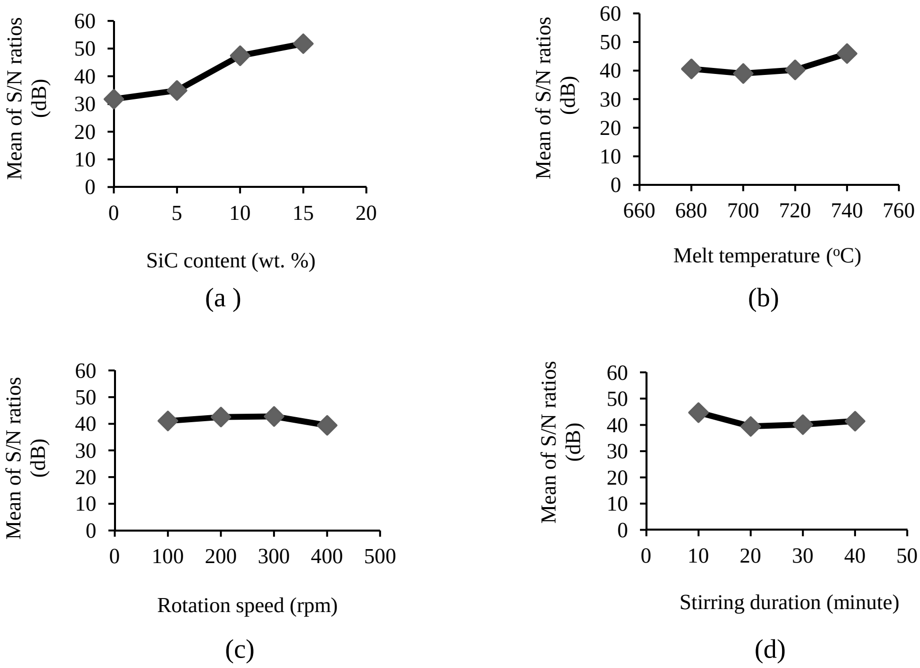


Fig. 4. The effect of process parameters on mean of S/N ratios (a) The effect of SiC content on mean of S/N ratios (b) The effect of melt temperature on mean of S/N ratios (c) The effect of rotation speed on mean of S/N ratios (d) The effect of stirring duration on mean of S/N ratios

On the temperature of melt controlling factor, the specific wear increases on the temperature from 680 until 700 ^{o}C, but above 700 ^{o}C the spesific wear decrease continuously into 0.0089 mm^3/kg.m on 740 ^{o}C temperature. S/N ratio on the highest temperature of the melt factor is 45.96 dB on the fourth variation, so the optimum specific wear is on 740 ^{o}C temperature. The increase of melt temperature from 680 to 740 ^{o}C made the aluminum matrix perfectly melting. On perfectly melting condition, the melt aluminum will easily spread on SiC particles surface. Evenly spreading of the aluminum melt on the SiC particles surface made the stronger interfacial bond between aluminum matrix and SiC particles. Besides, on perfectly melted aluminum matrix, SiC particles will be easier to evenly distribute when the stirring was conducted. Evenly distributed SiC particles and interfacial bond strength between aluminum matrix and SiC particles made the composite become harder and wear resistance.

In this study, the melt temperature of 740^{o}C made the pouring temperature on the mould become higher than pouring temperature on the melt temperature of 680,700 and 720^{o}C. The increase of the pouring temperature made the composite hardness increase [32]. The increase of the composite hardness will make the specific wear decreases. This study is consistent with studies conducted by Laurent et al [33], Hashim et al [34], Jayashree et al [35], which reported that increasing of the melt temperature will decrease the contact angle between the melt aluminum on the SiC particles surface. The smaller contact angle made the better wettability of the melt aluminum on the SiC particles, but increasing the temperature will lower the melt aluminum viscosity which cause SiC particles easily precipitate at the bottom of the crucible. Muttharasan et al [36] reported that increase the temperature of the composite matrix melt above 700^{o}C will increase Si content on the interface and increase their micro hardness.

The same way was conducted to analyse the effect of rotation speed on the specific wear composite. Plotting results show that the specific wear composite decrease from 0.0135 to 0.0118 mm^3/kg.m on the increasing of rotation speed from 100 until 300 rpm, but the specific wear increases until 0.0118 mm^3/kg.m on the rotation speed of 400 rpm. The highest S/N ratio obtained on the third variation 42.76 dB on the rotation speed 300 rpm. Based on S/N ratio, the optimum rotation speed in this research is 300 rpm.

The specific wear of the composite increased when the stirring rotation speed added from 100 to 300 rpm. Adding stirring rotation speed will increase centrifugal force which moves SiC particles in the aluminum melt from the center to the periphery crucible. However SiC particles movement will be stopped by the liquid aluminum. Centrifugal force of the liquid aluminum is smaller than centrifugal force of the SiC particles because density of SiC particles is bigger than density of aluminum. Centrifugal force value can be determined using the following equation: $F = m \times \omega^2 \times r$, where m is the mass of the SiC particle, ω is the rotating angular speed of the SiC particle and r is distance of SiC particle from the central axis of the crucible [37]. Increasing the stirring rotation speed will make the more evenly distribution of SiC particles on the composite matrix ([37], [38], [39]). High stirring rotation speed will cause gas bubbles were trapped on composite melt and formed the porosity. However, too high stirring speed would result in the high porosity and gas on the molten absorption of composites [40].

On the duration of stirring, increasing duration from 10 to 30 minute causes the specific wear increase from 0.0107 to 0.0143 mm^3/kg.m, but the specific wear decreases after 30 minute become 0.0118 mm^3/kg.m on the duration of 40 minute. The highest S/N ratio obtained first variation 44.73 dB, so the optimum duration in this research is 10 minutes. These results are consistent with studies conducted by Prabu et al [38], researchs stated that the optimum stirring duration is 10 minutes. At 10 minutes stirring duration, obtained more homogeneous SiC particles distribution in the aluminum matrix, but when the stirring duration increases above 10 minutes will increase gas absorbed in the composite melt and form porosity. The longer stirring duration can increase the absorption of gas in the liquid aluminum matrix and form porosity. However, increasing stirring duration certainly increases gas absorbability and oxidation of the prepared composites, which can decrease the mechanical properties [40].

Based on ANOVA (Analysis of Variance*)* as shown in Table IV, indicating that the most significant factor affected on the specific wear is SiC content with probability value of $P = 0.003 < 0.05$ with 95 % confidence level.

TABLE IV.
Analysis of Variance (S/N ratios)

Factors	DF	Adj SS	Adj MS	F	P
SiC content (wt. %)	3	0.001274	0.000425	69.21	0.003
Melt temperature (^{o}C)	3	0.000087	0.000029	4.7	0.118
Rotation speed (rpm)	3	0.00001	0.00003	0.45	0.737
Stirring duration (minute)	3	0.000028	0.000009	1.53	0.368
Residual error	3	0.000018	0.000006		
Total	15	0.001416			

Where DF is degrees of freedom, SS is the sum of squares, MS is the mean sum of squares, F is the F-ratio and P is probability factor.

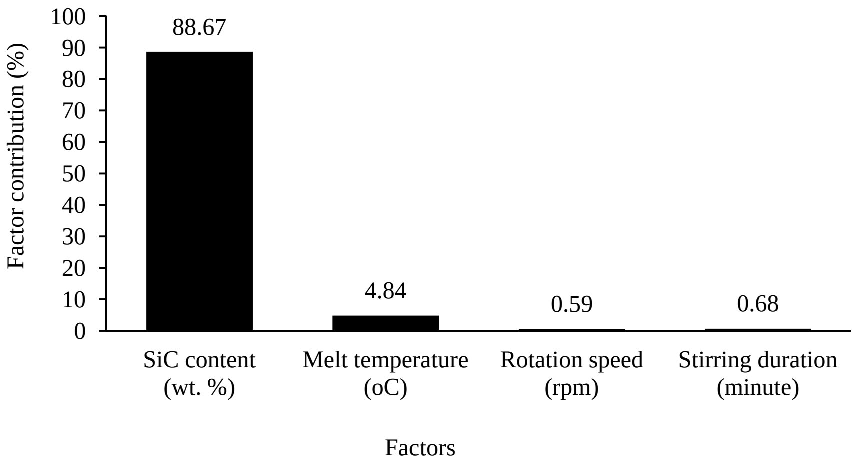


Fig. 5. Factor contribution on the specific wear

Contribution for each factors on the specific wear of Al-SiC composites is shown in Fig. 5. The biggest factor contribution on the specific wear is SiC content of 88.67 %, followed by melt temperature of 4.84 %, stirring duration of 0.68 % and rotation speed of 0.59 %. Based on the analysis of factors affecting specific wear and S/N ratio above, the optimum process parameters of stir casting are SiC content of 15 wt. %, melt temperature of 740 ^oC, rotation speed of 300 rpm and stirring duration of 10 minute.

B. Confirmation Test

Confirmation test is a stage to verify the conclusion of the experimental results. Once the optimum process parameters obtained in the experimental design, the final stage is to predict and verify the specific wear of composite using the optimum process parameters design. Calculation result on the optimums condition using MINITAB 16 software, specific wear (means) prediction ($\overline{Y}_{predicted}$) obtained on the optimum condition is 0,0033 mm^3/kg.m and S/N ratio is 60.64 dB. Table V shows a comparison between the specific wear predictions with the specific wear experimental verification using the optimum process parameters, which were SiC content of 15 wt. %, melt temperature of 740 ^oC, rotation speed of 300 rpm and stirring duration of 10 minute. There is very low difference between the specific wear of the verified experimental results with the specific wear prediction results of theoretical calculations using MINITAB 16 software. These results indicate that the optimum process parameters of the results selection can be used to predict the specific wear of Al-SiC composites produced by stir casting process.

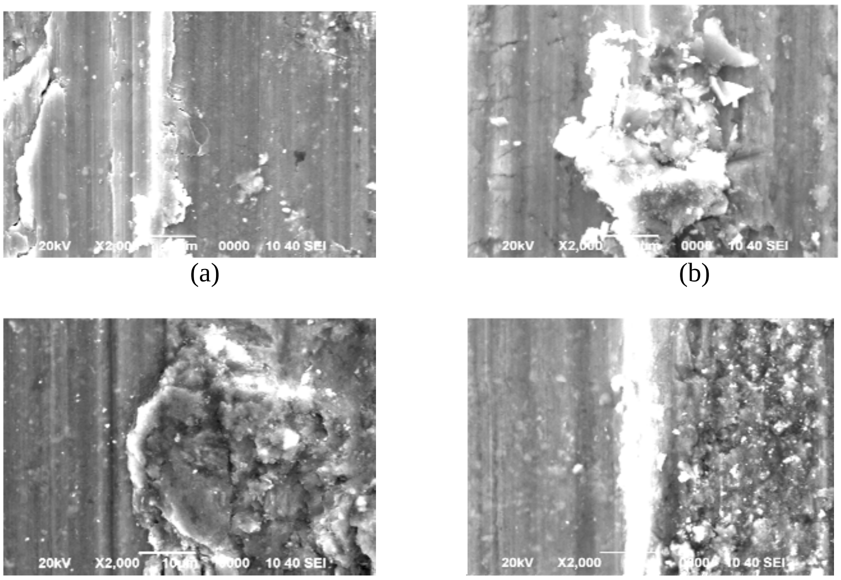
TABLE V.
Comparison between the Specific Wear Predictions with Specific Wear Experimental Verification on the Optimum Process Parameters Condition

The Specific Wear Experimental Verification (mm^3/kg.m)				**The Specific Wear Prediction (mm^3/kg.m)**	**Difference, $\overline{Y}_{predicted}$ - $\overline{Y}_{experiment}$ (mm^3/kg.m)**
Y_1	Y_2	Y_3	$\overline{Y}_{experiment}$	$\overline{Y}_{predicted}$	0.0019
0.0018	0.001	0.0013	0.0014	0.0033	

Where Y_1, Y_2, Y_3 is the specific wear test results (mm^3/kg.m) experimental verification of the conditions of optimum process parameters. $\overline{Y}_{experiment}$ is the average specific wear experimental verification

C. Microstructure Analysis

Microstructure of Al-SiC composite specimen was observed by scanning electron microscope (SEM). Microstructure observation was done to observe wear surface on Al-SiC composite specimen. Observation results of wear surface composite specimen shown in Fig. 6 (a-d) on different content of SiC. Microstructure of wear surface shows that increasing content of SiC from 0 to 10 wt.% make wear surface specimen become more rough visually, but in the condition SiC content of 15 wt. % wear surface specimen become smoother. Besides, the existence of SiC particles on the matrix cause specific wear on the composite surface become smaller because SiC particles is very hard. The increasing of SiC content on Al-Si matrix will significantly decrease specific wear because the SiC particles have high hardness so it can resist abrasion caused by the rolling steel disc.



(a) (b) (c) (d)

Fig. 6. Wear surface of Al-SiC composite specimen made by stir casting process on the condition melt temperature of 740 ^oC, rotation speed of 300 rpm, time duration of 10 minute and SiC content of : (a) 0 wt. %, (b) 5 wt. %, (c) 10 wt. %, (d) 15 wt. %.

IV. CONCLUSION

Experimental results show that the making of Al-SiC composites by stir casting process is successful. Adding content of SiC from 0 to 15 wt. % with grain sized SiC of 400 mesh on stir casting process can decrease specific wear of Al-SiC composites about 90.08 %. The same composites stir casting process, increase temperature of melt from 680 to 740 ^oC, it can decrease specific wear of 28.23 %. Increasing rotation speed from 100 to 300 rpm can decrease specific wear of 14.07 %, but increasing rotation speed from 300 to 400 rpm will increase spesific wear of 1.72 %. Increasing stirring duration from 10 to 40 minutes will increase specific wear of 10.28 %. The most significant factor affecting specific wear of Al-SiC composites is SiC content with contribution of 88.67 %. Optimum process parameters in this research is SiC content of 15 wt. %, melt temperature of 740 ^oC, rotation speed of 300 rpm and stirring duration of 10 minutes. Specific wear experimental verification value on optimum process parameters is 0.0014 mm^3/kg.m.

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AUTHOR PROFILE

Sadi was born in Pati, Central Java, Indonesia in 1971. He graduated with a Bachelor Degree in Mechanical Engineering from Gadjah Mada University, Yogyakarta, Indonesia in 1998 and received a Master Degree in Industrial Engineering from Sepuluh Nopember Technological Institute Surabaya, Indonesia in 2002. Then in 2012 he received Ph.D Candidate in Mechanical Engineering at Department of Mechanical and Industrial, Faculty of engineering, Gadjah Mada University, Yogyakarta, Indonesia. Since 1998 he has been a lecturer in the Department of Industrial Engineering at National Development University, Yogyakarta, Indonesia and served as Head of Manufacturing Process Laboratory in 2003-2009. His current research interests include metal casting, metal matrix composite and quality engineering.

Viktor Malau was born in Rianiate, North Tapanuli, Indonesia in 1957. He received a Bachelor Degree in Mechanical Engineering from Gadjah Mada University, Yogyakarta Indonesia in 1985. In 1993 he received a Master Degree in Genie des Materiaux from Ecole Centrale de Lyon, France and was awarded his Doctoral Degree (DEA) from the same university in 1996. Since 1986 he has been a lecturer, and served as Head of Material Laboratory in the Department of Mechanical and Industrial Engineering, Faculty of Engineering, Gadjah Mada University, Yogyakarta, Indonesia in 2009-2012. His current research interests include surface treatment and characterization and corrosion, and engineering materials.

Muhammad Waziz Wildan graduated his Bachelor Degree in Mechanical Engineering from Gadjah Mada University, Yogyakarta Indonesia in 1992. He received a Master Degree in Mechanical Engineering at Strathclyde University, United Kingdom in 1997 and was awarded his Ph.D from the same university in 2000 for zirconia-matrix composites reinforced with metal. Since 1994 he has been a lecturer, and served as Vice Chair of Postgraduate program in the Department of Mechanical and Industrial Engineering, Faculty of Engineering, Gadjah Mada University, Yogyakarta, Indonesia in 2001-2003. His current research interests include engineering materials, engineering ceramics and composites and energy management.

Suyitno graduated his Bachelor Degree in Mechanical Engineering from Gadjah Mada University, Yogyakarta Indonesia in 1995. He received a Master Degree in Material Science and Engineering at Delft University of Technology, Netherlands in 2000 and was awarded his Doctoral Degree from the same university in 2005. Since 1998 he has been a lecturer, and served as Vice Chair of Postgraduate program in the Department of Mechanical and Industrial Engineering, Faculty of Engineering, Gadjah Mada University, Yogyakarta, Indonesia in 2007-2009. His current research interests include casting and forming metallurgy, solidification technology and finite element method.