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MATERIAL REMOVAL MECHANISM AND SURFACE QUALITY IN MILLING OF SINTERED SOFT MAGNETIC COMPOSITES

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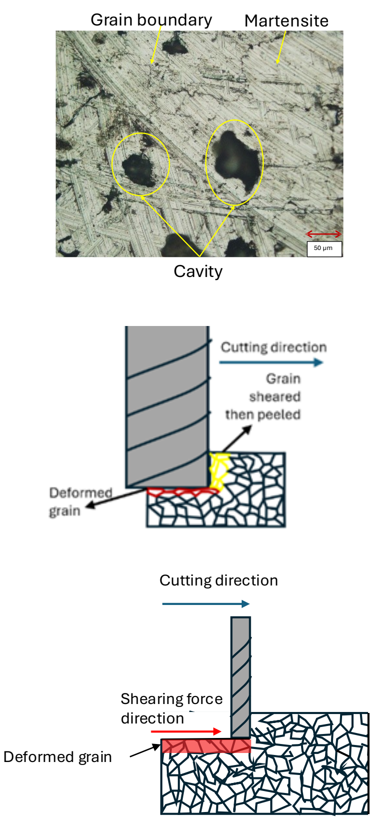
Graphical abstract



Abstract

Sintered Soft Magnetic Composites (SMCs) are widely used in electromechanical industries due to their favorable magnetic properties, such as high permeability and low hysteresis loss. However, their inherently brittle mechanical characteristics pose significant challenges during machining processes, particularly milling. This study aims to investigate the fundamental mechanisms of material removal during the milling process and to optimize machining parameters in enhancing surface quality under controlled and specified machining conditions. Milling experiments were conducted by cutting groove profiles in the workpiece for every set of varying parameters, which consisted of spindle speed, axial depth of cut, feed rate, and coolant usage as varying parameters, while radial depth of cut and tool path remained fixed. Surface roughness was analyzed using Response Surface Methodology (RSM) and Analysis of Variance (ANOVA). The surface morphology of machined surface is observed by using optical microscope. The results indicate that cooling conditions, spindle speed, and axial depth of cut affects significantly the machined surface quality, where the combination of spindle speed and axial depth of cut has a more significant effect than when considered individually. The smoothest surface roughness obtained from the experiment has surface roughness with Ra value of 1.42 µm. The surface morphology of the machined surface indicates that during milling, the surface material grains are deformed, leading to deformation-induced phase transformation, and it founds out that deeper axial depth of cut could result to smoother surface finish and coolant usage not always give smoother surface. This result confirmed that it distinct to the traditional wrought material machining.

Keywords: Machining parameters, material removal mechanism, milling process, soft magnetic composite, surface quality

1.0 INTRODUCTION

Soft magnetic composite (SMC) is a powder metallurgy (PM) material of iron-resin composite that has emerging utilization as a substitute for laminate materials for electrical machines such as electrical motors and generators [1]. SMC was developed to provide material with improved magnetic properties and electrical resistivity for electrical machines. SMC is made by mixing iron powder with a special resin binder, then it's poured into a mold for high pressure pressing process. At this state the formed SMC is not hard enough and the bond between each particle has not been firmly attached, thus it needs further heat treatment or sintering to harden the material and improve the inter-particle bonding [2]. The heat treatment also determines the mechanical and magnetic properties of the SMC [3].

SMC is designed to be manufactured into near net shape, which means after only the press molding process, the shape and dimension of the product are close to the final product and only need a minimum further manufacturing process, such as machining. However, the machining process is still often needed for making sharp edges, holes or any small profiles due to the difficulty of maintaining precision in the molding process [4]. Machining a sinter hardened PM material like SMC is challenging, due it has a significant different behavior compared to conventional wrought material [5]. Porosity in PM material is one of the problems that leads to rapid tool wear [6], it indicates poor machinability of PM material.

There are four theories based on the literature reported for the porosity effect on machining [7]. First, the micro-interrupted cutting theory, where the porosity in the material interrupts the continuous cutting on the micro level. Second is the hard-inclusion theory, where an undesired, more challenging phase exists in the soft metal matrix that causes sudden stress concentration when the cutting tool has contact with the hardened phase [8]. Third is deformation cutting theory, machining is defined as a deforming process when the cutting tool contacts and gives pressure to the workpiece, causing a layer of the workpiece to deform and then fracture into chips [9]. Sometimes the pressure given to the workpiece forms a harder layer on the machined surface that can cause cutting force fluctuation, which leads to rapid tool wear. Fourth is thermal conductivity theory, which is considered the most dominant theory for powder metallurgy machining [7]. The porosity on the PM material decrease the thermal conductivity, during machining process, the friction between cutting tool and workpiece generates heat. Reduced thermal conductivity, reduce the heat removal rates that causes quicker tool wear.

Machined surface quality relies heavily on the quality of the cutting tool, wear and damage of the cutting tool [10]. The stability during milling process influence the cutting tool condition, as an unstable machining induced chatter phenomenon that leads to rapid tool wear and damage [11]. The stability of milling process can be achieved by controlling the machining parameters[12], use suitable tool path strategy [13], apply suitable lubrication [14], and set suitable tool posture and position[15], [16].

The machined surface roughness is significantly increased when the cutting tool is worn and damaged. Therefore, rapid tool wear in PM material machining should be avoided. Another important aspect to be considered is the selection of the cutting parameter combination [17], which needed to be optimized for every different PM material machining, since each PM material has its own distinct characteristic based on the raw material and processing routes of the PM material.

Understanding the material removal mechanisms during machining provides valuable insights for selecting appropriate cutting parameters to achieve optimal surface finish. In the orthogonal cutting of powder metallurgy parts, the cutting tool serves several material removal mechanisms based on the current surface morphology and the depth of cut. The grain can be removed by peeling off, shear deformation, extruding or the combinations [18]. For the turn machine, the material removal is dominated by the shear deformation mechanism, that leads to the filling of the surface pores on the PM material[19].

Meanwhile, the published research on the milling process of PM material is not available while the utilization of PM material is rising for electrical machine and mechanical equipment. Therefore, the material removal mechanism of PM material during the milling is not well studied and there is no experimental evidence yet. This study will fill the current missing gaps in the milling process of PM material. The primary objectives of this study are to investigate the fundamental mechanisms of material removal during the milling process and to optimize the machining parameters to enhance surface quality under controlled with specified machining condition.

2.0 METHODOLOGY

The methodology of this study consists of four main stages: experimental setup, design of experiment, microstructure observation, and data analysis. In the experimental setup, cylindrical soft magnetic composite (SMC) material type Somaloy Prototyping Material (SPM) was machined using a vertical machining center with a carbide end mill under various parameter conditions. The design of the experiment followed a Box-Behnken Design (BBD), varying spindle speed, feed rate, axial depth of cut, and coolant application, while measuring surface roughness parameters using a surface tester. Microstructure observations were conducted using an optical microscope to examine the surface characteristics and phase composition of the machined areas. Finally, surface roughness data were analyzed using Response Surface Methodology (RSM) and ANOVA to identify significant factors and to propose a material removal mechanism during milling of the SMC material.

2.1 Experimental Set Up

In this study, SPM from Hoganas with a diameter of 120 mm and a thickness of 10 mm as a workpiece in the machining experiment. This material is a uniaxially compacted-sintered iron powder; the mechanical properties of this material are as shown in Table 1, as given in the material data sheet from the manufacturer. A machining experiment is conducted using the Leadwell V30 vertical machining center in the Engineering Workshop of the National Research and Innovation Agency of the Republic of Indonesia. A 2 mm carbide square end mill with 4 flutes is the selected machining tool in this experiment.

Table 1 Mechanical properties of Somaloy SPM

No.	Parameters	Values
1	Tensile Strength (MPa)	15
2	Yield Strength (MPa)	5
3	Young Modulus (GPa)	100
4	Poisson Ratio	0.23
5	Impact Energy (J)	1.3

2.2 Design of Experiment

This machining experiment was conducted by cutting groove profiles in the workpiece for every set of parameters, which consist of spindle speed, axial depth of cut, feed rate and usage of coolant as the varying parameters. Meanwhile the radial depth of cut and tool path remain fixed. The usage of coolant in this experiment is by the flood cooling method at On condition and without any coolant at Off condition. The value of varying parameters is determined by using a Box-Behnken design of experiment (BBD), a type of response surface design that does not encompass a full factorial design. BBD needs only three levels for each factor, that makes experiment using BBD less time and resource consuming[20]. A list of the parameters for the machining experiment can be seen in table 2. The base side of the machined surface is measured using Mitutoyo surface tester SJ-201 to obtain the surface roughness data. Three roughness value parameters are can be obtained as in Figure 1. Ra is the average of roughness profile deviation, Rz is the average distance of the five highest peaks to the baseline subtracted by the average distance of the lowest valley to the baseline, and Rq is the square root of the average distance of the measured profile to the baseline.

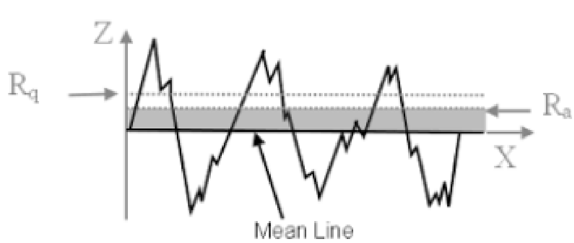


Figure 1 Surface roughness parameters

2.3 Microstructure Observations

The microstructure of each machined surface is obtained by using an Olympus BX51 optical microscope, the microstructure of the raw material is shown in Figure 2. It can be seen that the material is composed of ferrous particles that have boundaries amongst each other. The voids in the material are also seen with a size below 50 µm. Random brown layers on the material's surface indicated that rust has developed. The microstructure of this Somaloy material contains ferrite, austenite, martensite and pearlite phases, similar to the typical ferrous based powder metallurgy alloy [21].

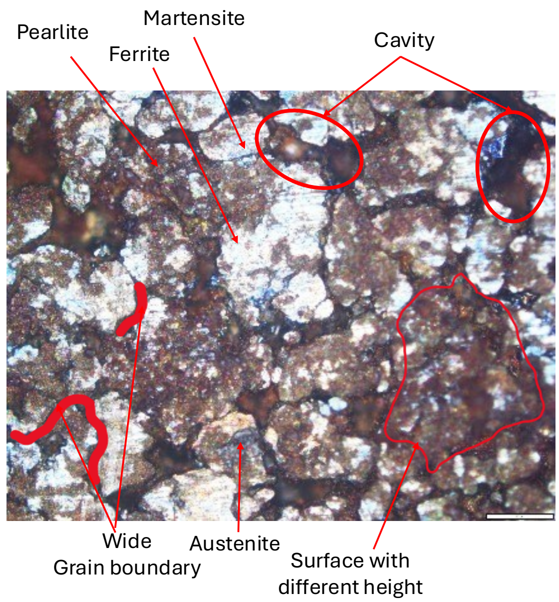
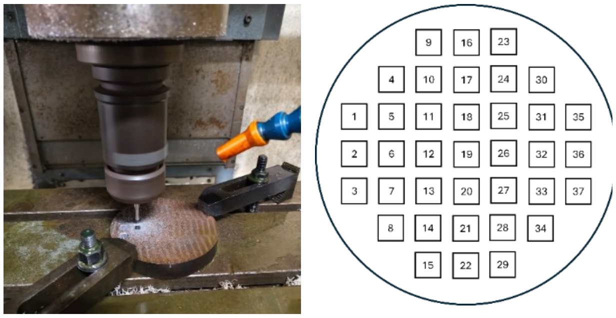


Figure 2 Microstructure of Somaloy SPM before machining

2.4 Data Analysis

The surface roughness is then analyzed by using RSM and analysis of variance (ANOVA) to obtain an understanding of which parameters significantly affect the surface roughness of the workpiece. These two analysis methods are used to validate the results against each other. The material removal mechanism model of milling SMC was then proposed by analyzing the microstructure of the machined surface. The experimental set up is shown in Figure 3.



(a) (b)

Figure 3 (a) Machining test experiment set up, (b) sample mapping

Table 2 Machining parameters list

Sample No.	Spindle Speed (RPM)	Feed rate (m/min)	Axial Depth of Cut (mm)	Coolant
1	2000	200	0.750	Off
2	1000	120	0.750	On
3	3000	120	0.750	On
4	1000	120	0.750	Off
5	2000	200	0.750	On
6	3000	120	0.750	Off
7	2000	40	0.750	Off
8	2000	40	0.750	On
9	2000	120	1.125	Off
10	3000	40	1.125	Off
11	2000	120	1.125	Off
12	2000	120	1.125	On
13	1000	200	1.125	On
14	2000	120	1.125	On
15	2000	120	1.125	On
16	1000	40	1.125	On
17	1000	200	1.125	Off
18	2000	120	1.125	Off
19	3000	200	1.125	Off
20	3000	40	1.125	On
21	3000	200	1.125	On
22	1000	40	1.125	Off
23	2000	200	1.000	On
24	3000	120	1.000	On
25	1000	120	1.000	Off
26	2000	40	1.000	On
27	2000	40	1.000	Off
28	3000	120	1.000	Off
29	2000	200	1.000	Off
30	2000	200	1.500	On
31	3000	120	1.500	On
32	1000	120	1.500	Off
33	2000	40	1.500	On
34	2000	40	1.500	Off
35	3000	120	1.500	Off
36	2000	200	1.500	Off
37	1000	120	1.500	On

3.0 RESULTS AND DISCUSSION

This section presents and discusses the results of the milling experiments on Somaloy Prototyping Material, focusing on surface roughness characteristics, surface morphology, and the underlying material removal mechanisms. The surface roughness measurements are analyzed to evaluate the influence of key machining parameters, including spindle speed, feed rate, axial depth of cut, and coolant application, with additional insights drawn from contour plots and ANOVA analysis. Microstructural observations are then used to examine changes in surface morphology across samples with varying roughness levels, revealing the role of grain deformation and phase transformation in the machining process. The discussion then turns to a proposed material removal mechanism model, derived from surface analysis and cutting trace observations.

3.1 Surface Roughness

Surface roughness is the most important quantitative parameter to evaluate the quality of the machined surface [22], The measured surface roughness is tabulated in Table 3. To understand the effects of each parameter on roughness, contour plots for two pairs of parameters on Ra roughness value are given in Figure 4 for milling without coolant on and Figure 5 for milling with coolant on. From these two figures, it can be seen that the surface roughness becomes smoother as the axial depth of cut becomes deeper, this verify the findings of previous research [18], where the machined surface of a ferrous green compact was smoother after a deeper orthogonal cut, due to plastically deformed surface particles subjected to greater pressure and cutting forces that integrated particle boundaries and filled the cavities on the material surface. Thus, the machined surface quality is improved.

While it is contrary to the findings on the turning of reinforced copper composite produced by powder metallurgy [23], in that study, as the depth of cut increased, the machined surface became rougher. It indicates that the turning mechanism was different from the milling mechanism of SMC. The reinforcement grain embedded in the PM copper composite has a significant higher hardness value than the base material and the cavities inside the PM materials, this creates a cutting force fluctuation during the turning process. Deeper depth of cut caused a higher cutting force fluctuation that led to quicker tool wear that affected surface quality significantly. This finding also confirmed by using other type of PM material [24].

Table 3 Surface roughness measurement results

Sample No.	Ra (µm)	Rz (µm)	Rq (µm)	Sample No.	Ra (µm)	Rz (µm)	Rq (µm)
1	4.52	30.87	6.3	20	3.59	20.82	4.81
2	4.88	30.99	6.61	21	3.79	24.01	5.14
3	5.07	28.44	6.72	22	3.89	26.3	5.74
4	4.9	31.53	6.74	23	4.3	31.06	6.44
5	2.85	21.64	4.46	24	2.91	19.05	4.23
6	4.14	28.43	5.94	25	3.72	29.09	5.69
7	5.12	33.17	7.19	26	4.11	30.58	6.09
8	2.7	18.98	4.07	27	4.5	27.8	6.16
9	5.66	34.52	7.48	28	2.35	17.03	3.57
10	4.12	28.64	6	29	1.42	11.98	2.14
11	4.67	28.07	6.29	30	3.48	23.15	5.15
12	2.84	22.81	4.29	31	2.34	16.66	3.56
13	2.32	18.27	3.43	32	2.37	18.47	3.59
14	3.69	26.14	5.39	33	2.48	20.01	3.84
15	3.53	23.58	5.14	34	3.78	22.29	5.04
16	4.58	34.11	6.88	35	3.78	25.99	5.34
17	4.05	28.49	5.83	36	4.47	29.44	6.18
18	5.3	32.31	7.07	37	3.65	23.06	5.09
19	5.41	35.34	7.82				

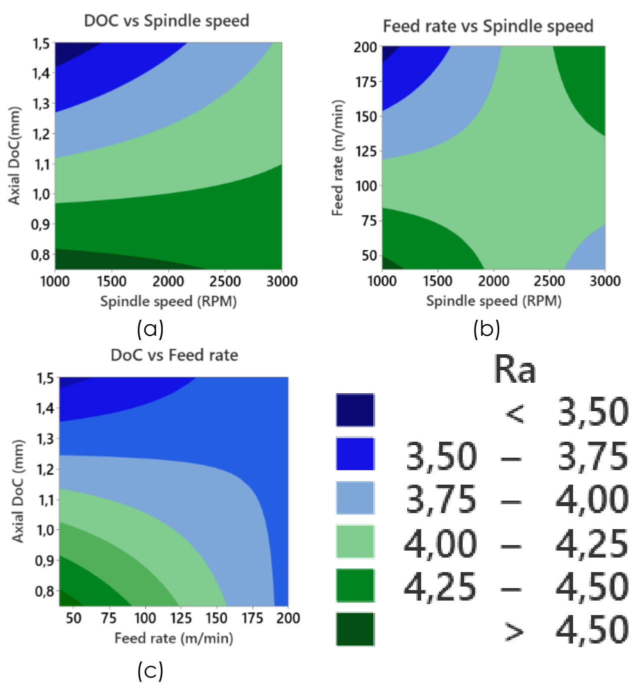


Figure 4 Contour plot of pairs cutting parameters to Ra roughness value without coolant

The spindle speed effect on surface roughness varies when it is combined with depth of cut, and when it is combined with different milling cooling conditions, either with coolant on or without coolant. The surface roughness was improved as the spindle speed increased when the feed rate was held at a specific value during milling with coolant on, while without coolant, the result was contrary. During dry milling, the increase in feed rate produces a smoother machined surface. Due to the plastic deformation during the cutting process, faster cutting speed induces smaller plastic deformation and decrease the buildup tool edge and burs that produced smoother machined surface [25].

However, the effect of plastic deformation to surface roughness is slightly different compared to orthogonal cutting in the cited reference, it is caused by the different cutting direction. The unidirectional cutting in orthogonal cutting produces uniform plastic deformation of the material in one direction and fill the surface porosity more uniformly, therefore resulting in smoother surface[18]. Meanwhile in milling, which the cutting tool is rotating and also moving in one or more direction causes more complex direction of plastic deformation, the change of direction causes varying plastic deformation and also can left off a buildup grain edge.

The effect of cooling has shown a significant positive effect to the surface roughness of milled SMC, it has similar behavior to the milling of wrought material [14]. The coolant removes heat more effectively and keeps the temperature of the cutting tool and the workpiece low that slowing down the tool wear, it is also related to the lowered vibration during the wet milling process.

Smoother surface roughness after wet milling in this study is the opposite of the findings in previous research that studied the effect of lubrication on the machining of sintered powder metallurgy material [26], where they found that the usage of coolant has negative effect to surface roughness of the machined workpiece. The reason is because during wet machining, there is some amount of coolant that trapped into the micro voids of the material that creates thermal shock caused by rapid cooling when the cutting edge sweeps coolant in the micro voids, it increases stress amplitude that fasten the degradation of cutting edge by high cycle fatigue.

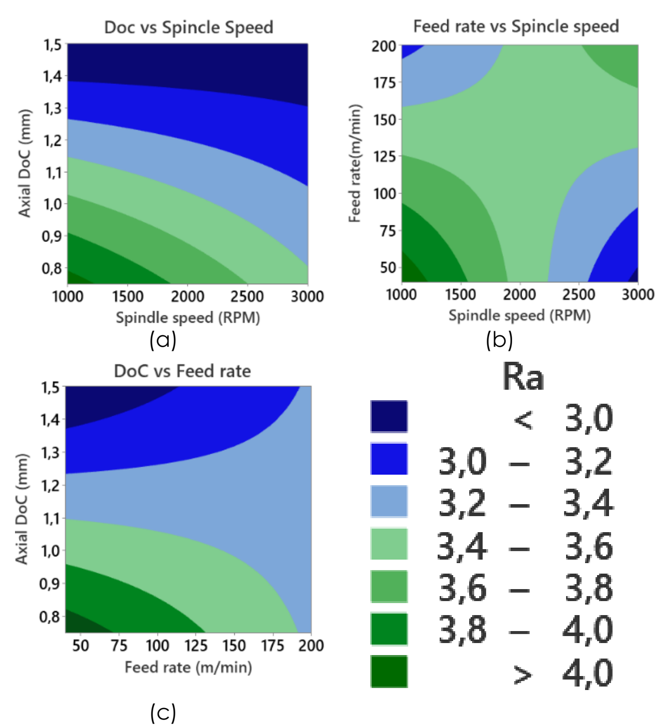


Figure 5 Contour plot of pairs cutting parameters to Ra roughness value with coolant

To understand which cutting parameters significantly affect the roughness of machined surface, analysis of variance (ANOVA) is conducted as shown in the Table 4. The p-value indicates the significance of a parameter to the response, in this case, the p-value limit is set to be 0.15 to reject the null hypothesis, that means there is 15% chance that the parameter has no significance to the response. Higher p-value limit than the traditional 0.05 is because the nature of milling PM material that has not been studied well, thus it better to consider higher null hypothesis probability, to get a direction to focus on in future studies[27].

The most significant parameter is the coolant condition during the machining, whether it was on or off, then followed by the depth of cut. Parameters combination of spindle speed with feed rate gives the lowest p-value of 0.231, although it is over the p-value limit of 0.15, which means it can be ignored as it is statistically insignificant, while other parameters combination has even higher p-values, which means any parameter combination is insignificant to the produced roughness of the machined surface.

Table 4 ANOVA result of the SMC milling test

No	Source	DF	Adj SS	Adj MS	F-Value	p-value
1	Spindle speed	1	0.0120	0.01199	0.01	0.920
2	Feed rate	1	0.2554	0.25538	0.26	0.704
3	Depth of Cut	1	2.6311	2.63106	2.70	0.126
4	Coolant	1	3.3319	3.33194	3.43	0.092
5	Spindle speed x feed rate	1	1.6110	1.61100	1.50	0.231
6	Spindle speed x Depth of cut	1	0.2297	0.22975	0.21	0.647
7	Spindle speed x coolant	1	0.2830	0.28300	0.26	0.612
8	Feed rate x Depth of cut	1	1.0434	1.04341	0.97	0.333
9	Feed rate x coolant	1	0.0336	0.03362	0.03	0.861
10	Depth of cut x coolant	1	0.0743	0.07428	0.07	0.794
	Error	26	27.8736	1.07206		
	Total	36	37.4419			

3.2 Surface Morphology

The machining process of soft magnetic composite PM material changes the morphology of its surface that can be seen in Figure 5 and Figure 6, it indicates the material removal mechanism during the machining process [18]. The Ra roughness parameter of the machined surface ranging from 1.42 µm at the smoothest to 5.66 µm at the roughest, almost five times the value of the smoothest surface. In Figure 6, the first three roughest surfaces have some similarities in the surface morphology. The first notable feature is that the gap between each somaloy grain is clearly seen, and the pores are wide and deep. The cutting tool left clear traces on the machined surface, indicating that the material was removed mostly by peeling off and shearing radially as the cutting tool moved during the machining process. The clear traces of the tool path in Figure 5 a, b, and c show that there is a significant height difference of the machined surface, while a clear gap among particles shows that the particle deformation had only slightly occurred before the particle was peeled off [18].

In figure 7, the first three smoothest surface also has similar surface morphology that distinguishes with the surface morphology in figure 6. The traces of more plastic deformation are clearly visible that fills the random cavity in the surface, and resulting to thinner boundary between each grain than unmachined surface in Figure 1.

Moreover, there is an indication of phase transformation of the workpiece material microstructure during the machining process using the designed parameters that affects the resulted surface roughness, as in the Figure 6 and Figure 7 shows that deformation by the shearing process is the dominating mechanism of this Somaloy machining. Deformation induced phase change of ferrous based material [25], [26]. Specifically, machining induced phase transformation by the generated heat causes a high rise in temperature, combined with high stress, which affects the active phase of workpiece material [28]. The difference in the surface roughness can be an indication of phase transformation of ferrous based metal, the martensitic phase transformation that induced by grain deformation, has a significant effect on surface roughening as it causes the coarse grains to become more inhomogeneous during the grain's plastic deformation [29], [30].

From the analyzed surface morphology, a smoother surface can be obtained where more intense plastic deformation occurred by deeper axial depth of cut while the phase transformation can be controlled to be more uniformly by utilizing coolant during the milling process.

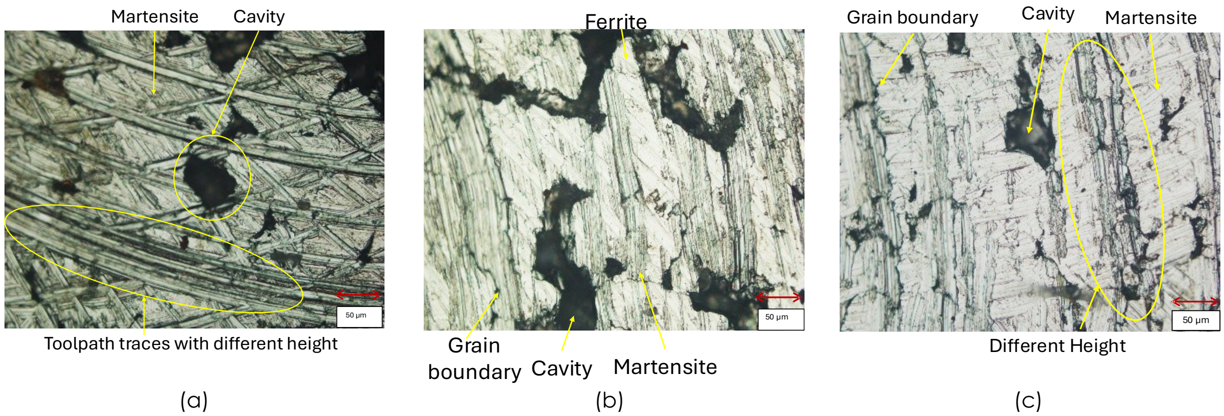


Figure 5 Microstructure of the machined surface with the first three roughest surfaces (a) Sample no. 9, (b) no. 19 , (c) no. 18

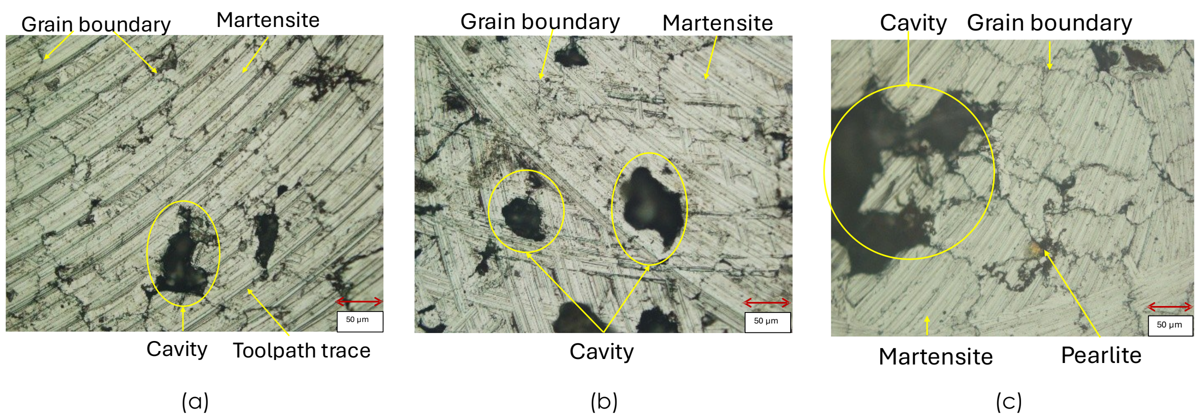


Figure 6 Microstructure of the machined surface with the first three smoothest surfaces (a) sample no. 29, (b) no.13 and (c) no. 31

3.3 Material Removal Mechanism

The material removal mechanism is illustrated in Figure 8. The milling cutter that rotates at a specific speed moves towards the cutting direction at a specific axial depth of cut. During the cutting process, the cutter gives pressure axially to the workpiece, it deforms the workpiece at the grain level axially, while the rotation and horizontal movement of the cutter remove the material by shearing, followed by peeling off the grain, this can be traced on the microstructure of the machined surface in Figure 6 and Figure 7, the grain shape is deformed following the rotation and horizontal movement of the cutter. Plucking material removal mechanism also occurred during the cutting process, as can be seen that there are pores that opened on the machined surface, which is the main indication that some of the grain was released from the surface wholly. More open pores on the machined surface result in a rougher surface, as they create more fluctuation during surface roughness measurement.

The yellow grain in Figure 8B illustrates the grain of powder material that was compressed, sheared, and peeled during the cutting process as the cutter moves toward the cutting direction. The indication of peeling mechanism was from the cutting debris of the workpiece, where the grain was agglomerated as it was removed from the workpiece. Some of the grains were stuck together after being compressed by the cutter, and then they peeled from the workpiece as the shear stress given by the cutter exceeded the material strength, the indication of material removed by mechanism is in the three smoothest machined surface in Figure 7. More material removed by peeling mechanism can improve the roughness of the machined surface as the deformed grain can close the pores, and decrease the height fluctuation that affecting roughness measurement [18], [31].

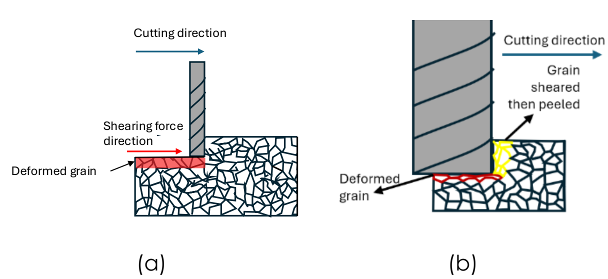


Figure 7 Material removal mechanism of Milling PM material Somaloy

4.0 CONCLUSION

These experimental results show that the milling behavior of Somaloy PM material has unique material removal mechanism that distinct with common understanding in conventional milling process. Among the machining parameters, cooling condition, spindle speed, and axial depth of cut were identified as having the most substantial impact on surface quality. Notably, the interaction between spindle speed and axial depth of cut plays a more dominant role in influencing surface roughness than each parameter individually.

Deeper axial depths of cut were found to produce smoother surface finishes. This phenomenon is closely related to the unique material removal mechanisms inherent to Somaloy PM during the milling process. The smoothest surface roughness recorded in the experiments was an Ra value of 1.42 µm, achieved under the following parameters: 1 mm axial depth of cut, 2000 rpm spindle speed, 200 m/min feed rate, and dry (no coolant) conditions.

Analysis of the surface morphology revealed that during milling, the grains on the surface of the Somaloy PM material undergo deformation, which may be linked to deformation-induced phase transformation. Additionally, the dominant material removal mechanism observed was shearing, which causes peeling of material grains. This process also includes grain pluck-off, leading to the formation of open pores on the machined surface.

The interplay between peeling and plucking mechanisms influences the resulting surface roughness. While the peeling and plastic deformed grain mechanism can improve surface finish by closing surface cavity and thinning the boundary of the grains, the plucking mechanism contributes to rougher surface by exposing and enlarging those cavity.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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