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# Impact of Machining Parameters on the Surface Roughness of Machined PU Block

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***Abstract*****—**Machining parameters are very important in determining the surface quality of any material. In the past decade, some new engineering materials were developed for the manufacturing industry which created a need to conduct an investigation on the impact of the said parameters on their surface roughness. Polyurethane (PU) block is widely used in the automotive industry to manufacture parts such as checking fixtures that are used to verify the dimensional accuracy of automotive parts. In this paper, the design of experiment (DOE) was used to investigate on the effect of the milling parameters on the PU block. Furthermore, an analysis of the machined surface chemical composition was done using scanning electron microscope (SEM). It was found that the surface roughness of the PU block is severely affected when PU undergoes a flood machining process instead of a dry condition. In addition the stepover and the silicon content were found to be the most significant parameters that influence the surface quality of the PU block.

***Keywords***—Polyurethane (PU), design of experiment (DOE), scanning electron microscope (SEM), surface roughness.

## I. INTRODUCTION

THE surface roughness in machining operation is an important aspect in the manufacturing industry as it will determine the quality of the product. To achieve such quality the proper machining parameters need to be carefully chosen to have a high productive operation. Among the parameters that may influence the surface roughness when dealing with materials with high hardness is the degree of tool wear because as tool wear increases, the surface roughness also will inevitably increase. On the other hand, soft material such as polyurethane (PU) block (PB) that is derived from polymer has a very low hardness and the tool wear is negligible. In milling machining, numerous parameters such as tool geometry that include the tool nose radius, flank width, run-out error and other parameters (cooling oil, cutting method) [1] and various cutting conditions including the depth of cut, feed rate, spindle speed, stepover and plunge rate can considerably affect the surface roughness (Ra). In another experiment, the influence of tool geometry on the surface finish in turning machining process of AISI 1040 steel was analyzed and it was found that the tool nose radius was the dominant parameter on the surface roughness [2]. In the range of material with low hardness, brass was used to investigate the surface roughness with a variation on the machining parameters and as a conclusion the value of the surface roughness was noted to increase proportionately with increase of tool diameter and spindle speed. Feed rate also played an important role when other parameters are constant [3]. Furthermore, design of experiment (DoE) was applied to optimize machining parameters of high purity graphite under dry machining in end milling [4]. In another study, the most influential and common sensory features for dimensional accuracy and surface roughness in computer numerical control (CNC) milling operations using three different material types were being investigated [5]. In material removal processes, an improper selection of cutting conditions causes surfaces with high roughness and dimensional errors, and it can generate a non-negligible level of vibrations [6]. Furthermore, in an investigation on surface roughness, it was found that the best surface finish was produced when the chip thickness is minimum with continuous chip and further observed that tool feed rate influences for the surface roughness of the workpiece [7]. A study on cutting speed revealed that when the cutting speed is increased during a machining operation, productivity can be maximized, and surface quality can be improved [8]. The surface finish of any material is defined by various parameters such as average roughness (Ra), smoothening depth (Rp), root mean square (Rq) and maximum peak-to-valley height (Rt) [9]. To achieve a good surface quality, the suitable parameters must be used but some industry players prefer to go through some try-outs to establish these parameters for a specific type of material and at the same time these try-outs increase the production cost [10], [11]. Another element that contributes to a better surface quality is the coolant. When dealing with ferrous material such as mild steel, the application of coolant is very important to decrease the building temperature between the tool and the workpiece during machining process and produce a better surface finish. In one investigation on Ti6Al4V, it was found that high cutting temperature in machining of this material usually leads to poor surface quality but when applying a cutting fluid it was able to control the cutting temperature. The drawback of this investigation is that it brings environmental and cost concerns coupled with an acceleration of the tool wears [12]. Moreover, coolant can also be used in flood condition where a large amount of fluid or coolant is directed towards the area where the high temperature is more likely to build up. On the other

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hand, a more common way of using the coolant is by small control amount that is also known as minimum quantity liquid (MQL). In another experiment, Ti6Al4V was once more used to investigate on the best type of coolant that is suitable to machine this material. As a result, a small amount that is typically less than 50 ml/hr was jetted into the cutting zone with a flow of compressed cold air.

In addition the applications of liquid nitrogen and air cooling were applied during the machining of Ti6Al4V [13], [14]. Dry, wet and air cooling cutting conditions on surface roughness were also studied related to AISI 1050 steel milling and it was found that surface roughness values were lower under air cooling condition than under dry condition, while higher than those under fluid cooling condition [15].

## II. Scanning Electron Microscope (SEM)

In the past few years the scanning electron microscope also known as SEM has become a very useful tool for research mainly when an in-depth investigation is needed on any types of material or living organism. In engineering, SEM is widely used in the analysis of surface structure. Chemical evaluation can also be evaluated by energy dispersive X-ray spectroscopy (EDX) that is attached to the SEM, namely SEM-EDX. There are three main types of signal that are produced by the SEM, namely secondary electron (SE), electron back-scattered diffraction (EBSD), characteristic X-rays and cathodoluminescence (CL).

In this paper, the method applied was the EBSD that focused on the study of deformation zones produced by machining. EBSD is a complementary characterization technique to analyse among others local texture, individual grain orientations, phase identification, strain analysis of polycrystalline materials [16]. In one study, EBSD method was applied combined with X-ray diffraction analysis, to study the changes in the crystallographic textures of aluminium single crystal in ultra-precision diamond turning operation. In a separate grooving experiment EBSD patterns were collected at various locations along the bottom part of the groove. These same patterns reveal a lattice rotation on the machined surface, which was induced by shearing in the cutting direction [17]. Moreover, an identical method was used in an investigation on the ground surfaces of austenitic stainless steel 316L. As a conclusion it was found that the EBSD patterns in the subsurface of the ground specimen denoted the presence of many slip bands and small angle grain boundaries in the region beneath the ground surface [18]. Damage on the subsurface was also being investigated by using the EBSD method and the material that was used is titanium alloys Ti-6Al-4V and Ti-834.The authors observed an intense slip bands couple with a change in alignment [19].

## III. Design of Experiment (DOE)

The DOE is an information gathering tool that helps to study the behaviour of some controllable variables in a process. An experiment can be defined as a test or series of tests where set of changes are made purposely to the input variables of a system or process so that observation can be made to the output and in the end identify the main or group of variables that is more influential. Experimentation is of utmost importance in technology commercialization and product development process which include new design and formulation, manufacturing process development, and also process improvement. The main objective in doing experimentation is to develop a better or robust process that is not so affected by external parameters. The DOE is also applicable in many non-manufacturing fields such as marketing, service operations, and general business operations. In the scientific field, experimentation is very important as it is considered as a scientific method for any research. In some scientific phenomena it is so well understood that some researchers by-pass the use of experimentation method. However, observation and experimentation of a process or system is the best way to understand and draw some conclusion on certain issues. The quality of an experiment is also important as a well-designed experiment can generate a model of system performance that can be applied to optimize a system. In general, an experiment is done to evaluate the performance of a system or process which includes a combination of operations, machines, methods, people, and other resources that changes the input into an output that contain in most cases one or more observable response variables. Moreover the variables are divided into two, namely the controllable and the uncontrollable [20].


Fig. 1 Milling process for car door checking fixture

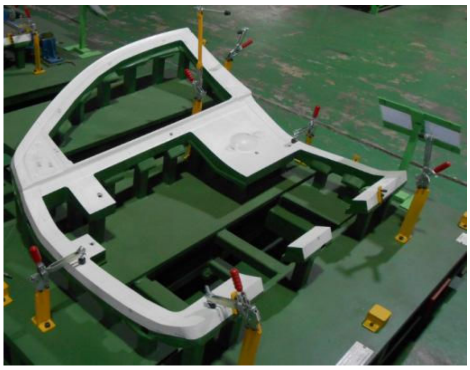


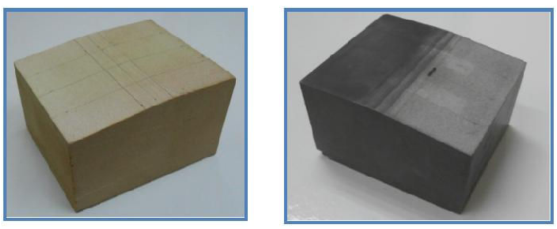
Fig. 2 Car door checking fixture ready for delivery

## IV. Materials and Equipment

A commonly used PB called Necuron 651 (N651) was used in this experiment. This material is mostly used in the automotive industry to manufacture checking fixture. Checking fixtures are used to check car components for dimensional accuracy. Fig. 1 shows a car door checking fixture undergoing a milling process in a manufacturing company whereas in Fig. 2 shows the same product that was ready for delivery. In this paper, Necuron 1001 (N1001) was also used on a trial basis to compare PB surface quality that have undergone a dry machining and a flood machining condition.

Machining of the PB is more challenging when the product is very complex such as having a curve profile where most manufacturers encounter some difficulties in applying the appropriate milling parameters to achieve a certain surface roughness as the PU surface structure contains a high degree of porosity and low hardness. Hence this paper focuses on issues related to milling machining process of curved PB profile. A specific design for the workpiece is as shown in Fig. 3, where PBs of the dimension 60 mm x 50 mm x 50 mm were machined for 16 experimental runs. The milling operation to produce the curve profile using a three-axis, vertical CNC milling machine (DMU 50 DECKEL MAHO) as shown in Fig. 4. It has a maximum spindle speed of 9,000 rpm together with a machining accuracy of 10µm. For the surface texture analysis, two equipment were used namely, a surface roughness tester (Mitutoyo Surftest SV-3100) and SEM-EDX (Hitachi S-3400N) with variable pressure setting.

All 16 experiments from the DOE were conducted using the N651. In the milling process, two different cutting tools were used, namely a 4-flute, flat end 10 mm diameter high speed steel (HSS) milling tool for roughing and a 2-flute ball nose 5 mm diameter HSS for finishing. The 16 PB workpieces were polymers that were considered to be low in density if compared to some ferrous material. Furthermore the mechanical properties of PB material had encouraged the experiment to make use of a standard HSS tool given also that the PB hardness is approximately 68 at the shore D, nearly the same hardness as certain grades of aluminum. Hence HSS cutting tool is suitable to be used in the experiment.



(a) (b)

Fig. 3 Experimental workpiece (a) Necuron 651 (b) Necuron 1001

In addition, the N651 has a flexural strength of 30 $N/mm^2$ and compressive strength of 26 $N/mm^2$ that minimises tool life problem as compared to ferrous material. PB is soft and easy to cut thus extending the tool lifespan. Another parameter that contributed to the good health of the cutting tool is the cutting speed that ranges between 3,100 to 3,300 rpm that prevents any high rise in the mean temperature. High speed steel or cobalt cutting tools are chosen for shorter production runs in non-ferrous materials and applications where machining conditions restrict the use of harder, more brittle substrates. These tools exhibit lower wear resistance and notably less heat resistance than carbide cutting tools [7].

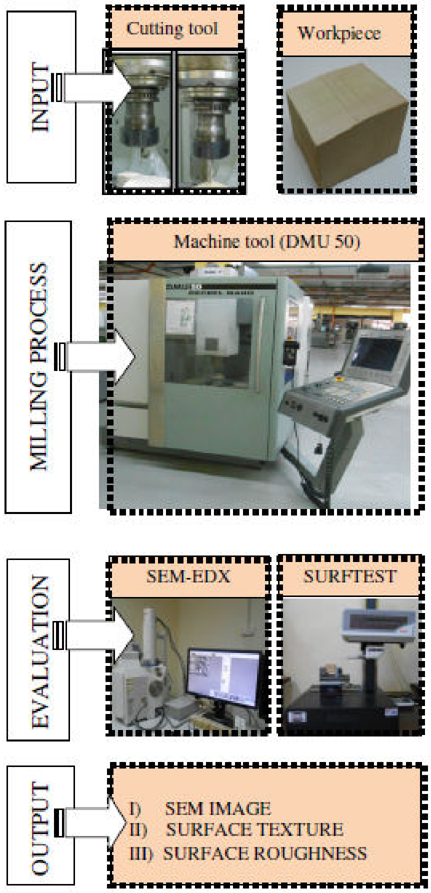



Fig. 4 Workflow of experiment

## V. Experimental Procedures

The methodology was divided into three phases. Phase one was the experimental slot where all 16 samples were machined according to the selected parameters. Phase two dedicated to the evaluation of the machined surface quality with the help of a surface roughness tester. The final phase saw the use of SEM-EDX to analyse both the machined surface structure and the chemical composition of each sample. In addition, all correlation analyses were carried out using MINITAB as the statistical software. DOE methodology used in this experiment was based on literature review. Suitability of DOE between PB and other test materials was also considered. To identify the most significant parameter for the surface roughness, the DOE of this research considered the milling parameters that included: (1) feed rate, (2) spindle speed, (3) depth of cut, (4) stepover and (5) plunge rate. Using these parameters, their impacts on the surface roughness of the PB were analysed. All these data were also used in the optimization stage. In other words it will be generated from a full experiment.

Table I shows all the five parameters that were used in this experiment at two levels, namely low and high. The type of DOE used was a half fractional factorial with five parameters that delivered 16 runs with three repetitions on the surface roughness measurement as shown in Table II.

TABLE I
PARAMETERS AND LEVELS FOR THE DESIGN OF EXPERIMENT

| Control Parameters | Unit | Symbols | Levels: Low (-ve) | Levels: High (+ ve) |
|---|---|---|---|---|
| Depth of cut | mm | A | 0.10 | 0.20 |
| Feed rate | mm/min | B | 400 | 600 |
| Stepover | mm | C | 0.18 | 0.25 |
| Spindle speed | rpm | D | 3200 | 3400 |
| Plunge rate | mm/min | E | 150 | 300 |

The machining parameters as indicated with alphabets in Table II are A: depth of cut, B: feed rate, C: stepover, D: spindle speed and E: plunge rate. Three types of tools were used in this experiment namely, a face milling cutter for the squaring process of the block, followed by the roughing process that was done with a 4-flute, 10 mm diameter HSS flat end cutting tool and ended with the finishing process with a 2-flute, 5 mm diameter HSS ball nose cutting tool. Previous trials on PB workpieces with different densities underwent the same milling processes under flood machining conditions proved to differ in term of surface roughness mostly due to the high rate of absorption by PB materials due to PB having high porosity. Thus a dry machining condition was preferred in order to achieve a more stable surface quality.

TABLE II
EXPERIMENT RESULTS

| Exp. No. | Parameters: A | B | C | D | E | Surface roughness (µm) |
|---|---|---|---|---|---|---|
| 1 | 0.10 | 400 | 0.18 | 3200 | 300 | 8.39 |
| 2 | 0.20 | 400 | 0.18 | 3200 | 150 | 8.78 |
| 3 | 0.10 | 600 | 0.18 | 3200 | 150 | 7.28 |
| 4 | 0.20 | 600 | 0.18 | 3200 | 300 | 8.41 |
| 5 | 0.10 | 400 | 0.25 | 3200 | 150 | 12.70 |
| 6 | 0.20 | 400 | 0.25 | 3200 | 300 | 10.60 |
| 7 | 0.10 | 600 | 0.25 | 3200 | 300 | 13.71 |
| 8 | 0.20 | 600 | 0.25 | 3200 | 150 | 12.81 |
| 9 | 0.10 | 400 | 0.18 | 3400 | 150 | 12.65 |
| 10 | 0.20 | 400 | 0.18 | 3400 | 300 | 6.34 |
| 11 | 0.10 | 600 | 0.18 | 3400 | 300 | 7.20 |
| 12 | 0.20 | 600 | 0.18 | 3400 | 150 | 10.30 |
| 13 | 0.10 | 400 | 0.25 | 3400 | 300 | 6.71 |
| 14 | 0.20 | 400 | 0.25 | 3400 | 150 | 11.40 |
| 15 | 0.10 | 600 | 0.25 | 3400 | 150 | 14.90 |
| 16 | 0.20 | 600 | 0.25 | 3400 | 300 | 10.92 |

**Note:** Exp. No. = Experiment number

## VI. RESULTS AND DISCUSSION

The main objective of this experiment was to identify the most significant parameter and the chemical element that have an impact on the surface roughness. Initial trial on N1001 was carried out to evaluate the impact of using a flood cooling and dry milling machining conditions. Preliminary experiments showed that dry machining resulted in better surface roughness quality as compared to flood machining condition. The coolant (flood machining condition) affects the surface roughness of the PB mainly due to the high porosity of this material that seems to absorb the coolant and cause a distortion on the machined surface. It is strongly supported with the high amount of oxygen that is 16.76 wt% compared to 11.96 wt% (Fig. 5 and Table III) when machined without coolant.

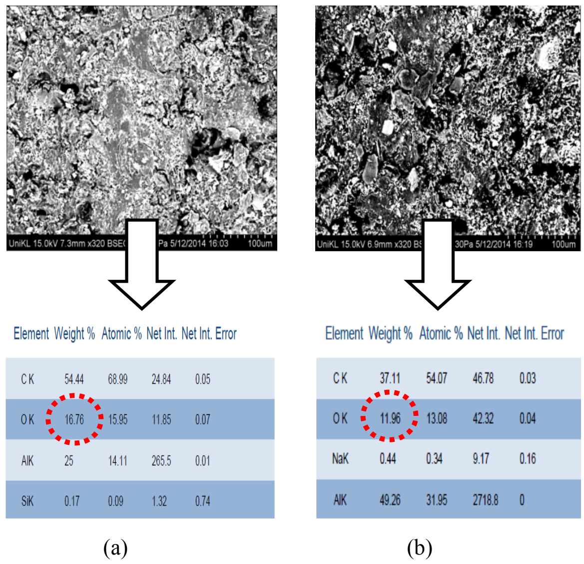



Fig. 5 SEM-EDX imaging and chemical content of (a) machining with coolant (b) machining without coolant **Notes:** 1) "K" - K shell energy level 2) Weight % - Ratio of the weight of the element to the weight of the sample 3) Atomic % - Ratio of the number of atoms of the element to the total number of atoms in the sample 4) Net Int. – Average intensity of X-ray in kilo count per second (kcps)

TABLE III
CHEMICAL ELEMENTS AND FACTORS

| **Chemical Elements** | **Symbols** | **Levels (% Weight): Low (-ve)** | **High (+ ve)** |
|---|---|---|---|
| Carbon | C | 40 | 75 |
| Oxygen | O | 10 | 50 |
| Sodium | Na | 5 | 40 |
| Silicon | S | 0.02 | 25 |
| Aluminum | Al | 0.1 | 50 |

Based on this finding, machining experiments were then done under dry milling condition so that better surface roughness quality could be recorded. After applying the DOE and surface milling operation, the surface roughness readings were measured and recorded, as shown in Table II.

The stepover in milling is defined as the between two neighboring passes. The minimum surface roughness, hence the highest achievable surface quality recorded was at 6.34 µm, with the minimum stepover value at 0.18 mm. The worst surface quality value at 14.90 µm (Table II) was recorded when the stepover was at its highest value at 0.25 mm.

The second most significant parameter that has an impact on the surface quality was the plunge rate. In most material this particular parameter was very critical and it was independent on the hardness of the material. Its highest condition was at 300 mm/min, recorded a surface roughness value at 9.03 µm, as shown in Fig. 6. It was not so significant when compared to the stepover. However, the surface roughness value is quite important. In principle, the larger distance value, the higher will be the surface roughness value.

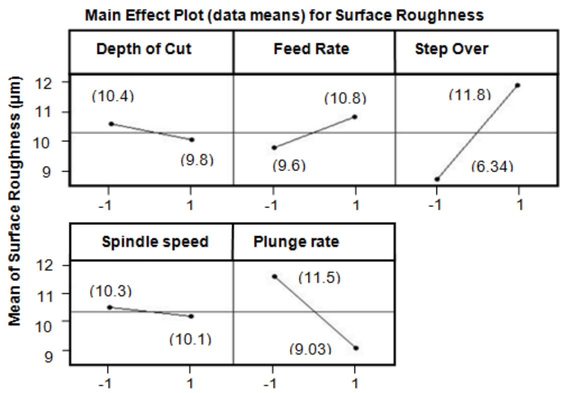



Fig. 6 Graph of the significance of machining parameters

The third in the ranking was the feed rate, the milling parameter that also had an impact on the surface quality. Feed rate effect on surface roughness was not as significant as the plunge rate or the stepover. Fig 6 shows a trend from the feed rate where a better surface roughness could be achieved with feed rate value was set below 400 mm/min. The machining time will undoubtedly be much higher that will result in a nonproductive machining process.

Depth of cut in this experiment did not have a significant impact on machining of PB. Based on literature review, depth of cut has a much important effect when dealing with material with much higher hardness such as mild steel.

Finally, the spindle speed also did not have a significant effect on the surface roughness when compared to the other milling parameters. As shown in Fig. 6, at a lower spindle speed setting, the surface quality was 10.1 µm and at a higher setting, the surface roughness was at 10.3 µm.

To sum up, the DOE experiment has shown that stepover is the most significant parameter in machining the PB under a dry machining condition.

The next finding was on chemical analysis of the PB. It was to establish whether chemical elements in PB have any impact on the surface quality. Based on Fig. 7, silicon appears to have a very significant impact on the surface roughness compared to the other elements. When silicon was at its lowest level, in the PB machined workpiece, the surface roughness value was low, at 4.5 µm (Fig. 8). At its maximum value, the surface roughness value was high, at 12.5 µm. In steel, silicon plays some very important role such as to prevent oxidation that contributes to material strength and hardness.

The presence of silicon in PB that is above 0.02 wt% seems to affect the surface quality as this element will create abrasive particles that will either affect the tool quality or the hard particle will be chipped off the machined surface leaving behind a significant pore that will contribute to a bad surface quality. In addition, the higher the content of silicon on the machined surface of the PB, the higher will be the surface roughness as more silicon particles are pulled out during the milling process.

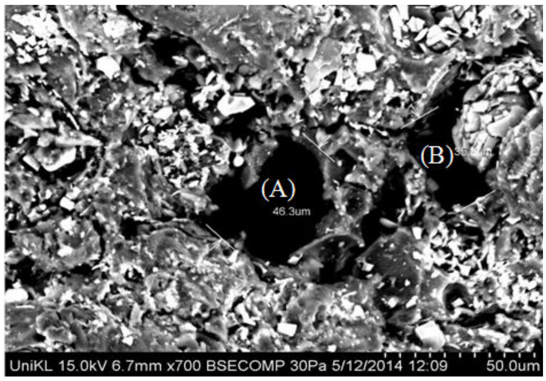



Fig. 7 SEM image of machined PU block with high porosity

The graph shown in Fig. 8 also reveals that sodium is the second most significant element in machining PB, at its lowest percentage the surface roughness achieved 6.5 µm and 10.5 µm at its highest. The inclusion of sodium in the PB is mainly to prevent any heat expansion agent as the PB is a thermoset material that cannot be recycled and even if a high heat is apply to it, the material eventually crack but not melt.

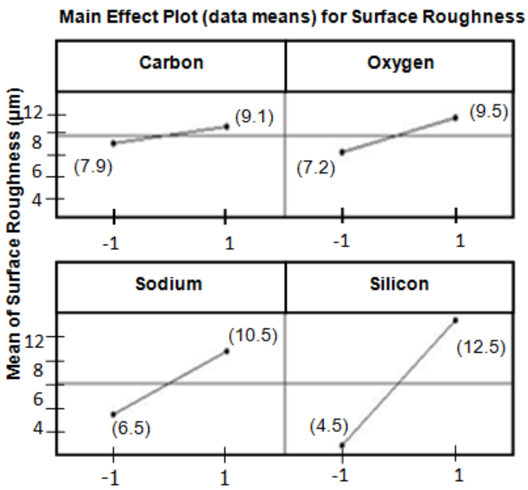



Fig. 8 Graph of the significance of the most common chemical elements on the surface roughness

The machined surface of one of the workpiece is shown in Fig. 7 where the pores can clearly be seen. The biggest pore was 46.3 µm (A) and the second one was 35.8 µm (B). The existence of pores of such a magnitude contributes mainly in an increase of the surface roughness that once more confirms that the PB contains a high level of porosity. In addition, if these types of pores are located on the measured location, this will result in a very high surface roughness. Moreover as stated earlier, high concentration of porosity couple with a significantly high diameter will undoubtedly absorb the coolant that was shown to create some distortion on the surface quality.

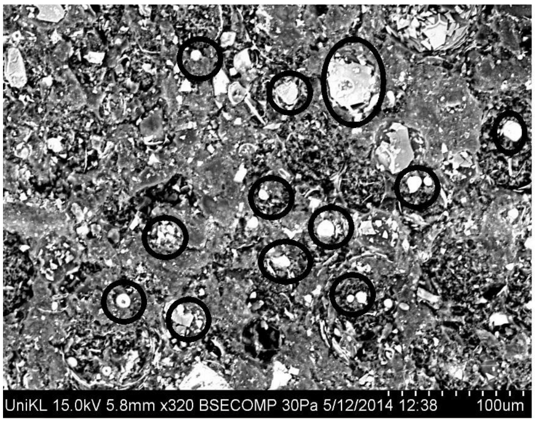



Fig. 9 SEM image of machined PU block with high concentration of silicon

The experiments had shown that silicon affect the surface roughness due to its high concentration in some area as shown in Fig. 9. The presence of silicon in some materials is mainly to strengthen the material but during the machining process it presence may cause partial or fully chipping off workpiece surface. This situation results in creating pores that will also contribute in a high surface roughness value, hence lower surface quality.

## VII. Conclusion

The research experiments and analysis on the PB using the DOE and MINITAB were carried out to identify the most significant parameter and chemical element that has significant impact on the surface roughness, it was concluded that the variations in stepover values have considerable influence on the machined surface quality. Highest achievable surface quality recorded was at 6.34 µm, with the minimum stepover value at 0.18 mm (Table II). SEM-EDX that was used to analyse the chemical content of the PB showed that four elements namely sodium, silicon, carbon and oxygen were the most common elements in PB, with silicon contributed the most significant impact on PB surface quality.

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