# ISSUES IN MACHINING EPOXY RESIN - NANO REINFORCEMENT COMPOSITE SYSTEMS WITH RESPECT TO SURFACE INTEGRITY AND TOOL WEAR

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**Abstract**

Polymer nanocomposites, reinforced with nanoparticles such as $SiO_2$, are gaining attention due to their improved mechanical properties. However, the impact of $SiO_2$ nanoparticle content on machining processes, particularly tool wear and surface quality, remains insufficiently explored. This study investigates the effect of different $SiO_2$ concentrations (0–8 wt.%) on tool wear ($V_B$), surface roughness ($R_a$), and chip formation during the micromachining of epoxy-based composites. Samples were fabricated with varying $SiO_2$ content and machined using a micro-milling process. The tool wear and surface roughness were evaluated at regular intervals, with the wear predominantly occurring within the first few minutes of cutting. Results show that as the $SiO_2$ content increases, tool wear accelerates, leading to higher surface roughness. In particular, the addition of $SiO_2$ contributed to the formation of non-dispersed clusters, which exacerbated tool wear. The chip morphology shifted from worm-like to crumbly as tool wear increased, reflecting the progressive degradation of the machining process. These findings suggest that while higher nanofiller content may improve material strength, it significantly impacts the machining efficiency and surface quality, particularly when filler dispersion is poor. The study highlights the importance of optimizing the dispersion of nanofillers to maintain machining stability and surface integrity. This research provides insights into the micromachining behavior of $SiO_2$-reinforced nanocomposites and serves as a foundation for further investigations into the machining of advanced composite materials.

**Keywords:** Nanocomposites, nanoreinforcement, micromilling, tool wear, surface roughness

## 1. INTRODUCTION

Polymer systems are widely used due to their unique properties, such as ease of manufacture, light weight, high structural strength and more. They are used in a wide range of applications – from the aerospace and automotive industries to objects of everyday use. However, polymers have a lower modulus of elasticity and strength compared to metal and ceramic materials. One way to improve their mechanical properties is to reinforce polymers with inclusions (fibers, platelets or particles). Currently, developments are underway in the use of nano-reinforcements and the production of nanocomposites. Experimental investigations point to the occurrence of new phenomena capable of noticeably influencing the properties of the resulting composite - an increase in strength when using relatively small amounts of reinforcement [1, 2]. Also, reducing the size of these components to the nanometer level causes an improvement in the mechanical and physical properties of the composite due to the presence of a large number of nanoparticles (large specific surface area of the reinforcement) [3]. One of the most desirable nanoparticles is $SiO_2$, which is inexpensive, non-toxic, biocompatible, highly thermally and mechanically stable, and particularly effective as a mechanical reinforcement. All these aspects make it an ideal choice for filler in composites. The size of spherical $SiO_2$ nanoparticles alone is around 20 nm. The disadvantage of this filler is the high hydrophilicity of the $SiO_2$ surface, which causes the aggregation of nanoparticles that are then difficult to disperse in the polymer matrix [4, 5, 6, 7].

With the development of polymer nanocomposites and their applications in various industries, it was necessary to be able to tailor the nanocomposites themselves to the design specifications. Regardless of where these products are ultimately used, some of the finishing machining operations associated with the growing production of composite parts cannot be dispensed with. However, unlike metal parts, composite systems behave differently in machining due to their material structure [8, 9]. These properties mainly affect tool wear, which has an impact on the quality of the machining process and the resulting quality (roughness) of the machined surface [10]. The machining of composite systems is now well described. Nevertheless, new studies are still appearing that address the issues of tool wear, optimization of machining conditions, delamination and the character of the workpiece surface. A noticeable drawback of the application of nano-strengthening is the still insufficient understanding of the synergy of the individual phases [11].

## 2. MATERIALS AND METHODS

As a matrix to produce composite samples, the two-component low molecular weight epoxy resin ChS-EPOXY 520 was chosen. To cure the resin, P11 hardener was used, added in a weight ratio of 100:11. To produce the samples, a discontinuous process of casting the material mixtures into a pre-prepared mould was chosen, which was made of two-component silicone rubber Silastic T1. Silicone rubber was chosen for the mould production due to its ease of production and easy handling. The mould did not need to be separated, the samples could be easily removed, and the mould did not require complicated cleaning. The dimensions of the samples were chosen according to the requirements for the subsequent micromachining operations. The filler used was the pyrogenic amorphous silica LM- 150 Cab-O-Sil. The material is amorphous, highly pure, with a large specific surface area (150 $m^2$/g). It was added to the epoxy resin in proportions of 0, 2, 4, 6, 8 wt.%. A hardener is then added. The mixture thus prepared is mixed well and poured into the mould. The mould is placed in a pressure vessel and the mixture is cured for 24 hours at a laboratory temperature of 22 °C and a pressure of 0,7 MPa. To achieve the final values of the mechanical parameters it is desirable to cure at 50 °C for 10 hours. The basic sample dimensions were 30x10x10 mm.

The DMG MORI CMX 600 V machine was used to machine the samples. Before starting the machining process, the samples were clamped longitudinally to the direction of the tool path in a clamp and angled. The cornering was followed by end-plane micro-milling, which was carried out according to the defined cutting conditions, see below. The control criterion for evaluating the amount of wear incurred was a tool time interval of 5 minutes in the cut corresponding to a machined area of 300 $mm^2$.

The tool used for the experiment was 2ALE-005-005-S04, a double-edged cylindrical sharp cutter with a diameter of 0.5 mm and a length of 40 mm suitable for machining soft plastics and composite materials (**Figure 1**). The machining experiments were carried out using cutting conditions as recommended by the cutting tool manufacturer. The main parameters were: spindle speed n=12 000 [$rev.min^{-1}$], feed per tooth $f_z$= 0.01 [mm], depth of cut $a_p$=0.033 [mm], width of cut $a_e$=0.20 [mm].

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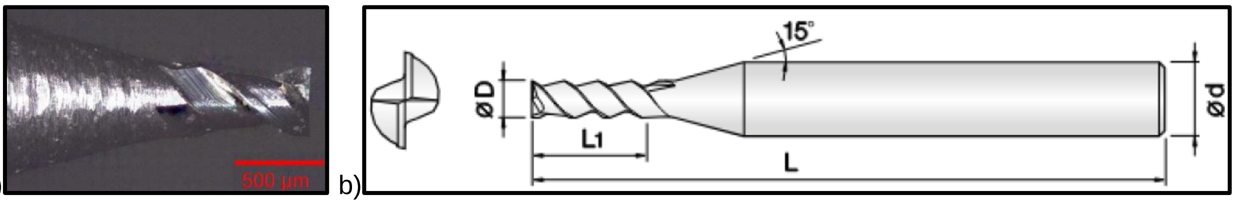



**Figure 1** Milling cutter 2ALE-005-005-S04. (**a**) Detail of cutting geometry. (**b**) Scheme of basic parameters of the cutter

For the evaluation of the monitored parameters - tool wear ($V_B$), surface roughness ($R_a$), surface integrity (burrs, cavities, etc.) and the nature of the resulting chips, a confocal microscope Keyence VK-X1100 was used using a set of objectives with a zoom range of 5x to 100x. The controlled parameters were monitored after 5 minutes of the instrument in the cut. A total of 6 comprehensive measurements (30 minutes of instrument in section) were performed. In the course of evaluation of the achieved quality of the machined surface, the occurrence of cavities, unmachined areas, filler clusters and other phenomena associated with machining of nanocomposite materials based on particle reinforcement was observed. A summary of the occurrence of cavities, clumps and others is shown within the sample subsections along with the final surface at the end of the experiment and the chips taken.

## 3. RESULTS

The sample without the addition of reinforcing nanoparticles, Sample 1, acts as a basic reference for the observation of the observed parameters. It is therefore a pure epoxy resin made according to the methodology presented in Chapter 2. **Figure 2** shows the processed values of the observed tool wear parameter $V_B$ for machining samples with 0, 2, 4, 6 and 8 wt.% $SiO_2$. Similar is the case for **Figure 3** for the parameter $R_a$. The individual plots will be described within the sub-sections corresponding to the sample under examination.


**Figure 2** Summary graph of achieved $V_B$ parameter values for individual samples

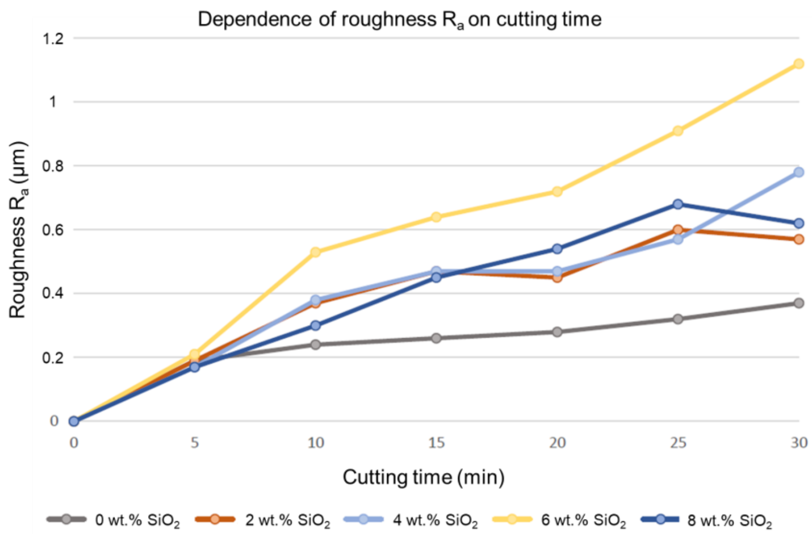
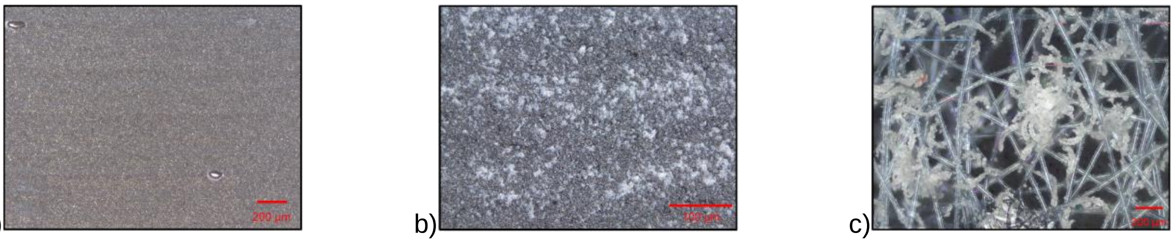



**Figure 3** Summary graph of achieved $R_a$ parameter values by each sample

### 3.1 Sample 1 – 0 wt.%

In **Figure 2** the wear development of the tool can be observed. When the sample was machined without the addition of nanofiller, almost 80% of the total wear occurred within the first 5 minutes of milling. The wear trend was of increasing character, except at the points corresponding to 10 and 25 minutes in the cut. These decreases were due to the difficulty in positioning the microtool to the initial measuring positions and the presence of post-machining debris (chip clusters) that can visually act as cutting tool material. The dependence of roughness on tool time in cut for Sample 1 (**Figure 2**) shows a slight increasing trend along with increasing magnitude of $V_B$ wear. This can be explained by the area of the sample in which the material may have been ploughed resulting in an increase in the surface roughness, by the deposition of a larger amount of very fine particles of chips or by the greater presence of cavities in the sample. The machining cycles revealed the presence of cavities in the sample (**Figure 4a**), that were created during the production of the blanks for the experimental part, e.g. by insufficient venting during casting. These cavities may increase tool wear due to the interruption of smooth tool engagement. Furthermore, a material surface can be observed where, due to tool wear, ploughing of the material has started to occur and the chip thus separated has then attached to the machined surface (**Figure 4b**). The machining of the specimen, which contains only epoxy resin, produced worm-like chips (**Figure 4c**). The same chip morphology was present during the last machining cycle.

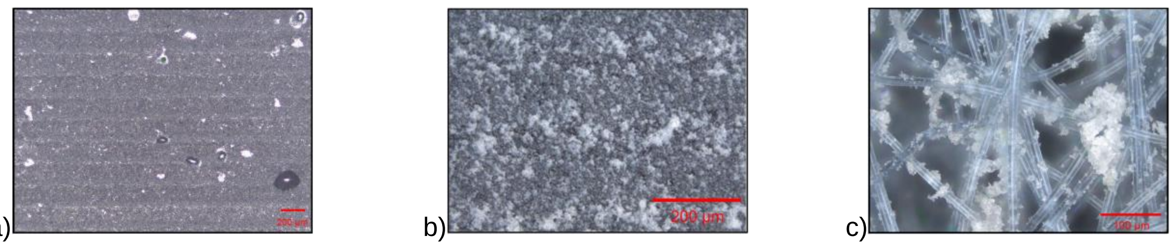


a) b) c)

**Figure 4** Overall overview of Sample 1. (**a**) Occurrence of cavities on the surface.; (**b**) Surface after 30 minutes of the tool in the cut.; (**c**) Nature of the chips formed – white areas.

### 3.2 Sample 2 – 2 wt.%

As with Sample 1, the greatest wear occurred during the first machining cycle, with approximately 74 % of the total wear (**Figure 2**). The trend of the curve is increasing and the differences between the measured sections are almost constant. Contrary to expectations, the total wear is approximately 5 μm less than the tool that milled the sample without nano-reinforcement. A regular increase in $R_a$ values can be observed in the roughness plot (**Figure 3**). However, it is clear from the roughness measurements that the resulting surface of Sample 2 has lower $R_a$ values than Sample 1. When machining the samples with $SiO_2$ addition, it was possible to observe clusters of undispersed nanofiller (white areas) in addition to cavities (black areas) (**Figure 5a**). The quality of the machined surface and the recognizability of the toolpaths also rapidly decrease due to the increasing magnitude of tool wear (**Figure 5b**). After adding 2 wt.% $SiO_2$, the character of the resulting chips did not change much. Their shape is still worm-like. After the last machining cycle, i.e. 30 min, there was a relatively large change in the nature of the chips. Due to tool wear, the shape of the chips changed from worm-like to a crumble shape, which forms accumulations of chips (**Figure 5c**).



a) b) c)

**Figure 5** Overall overview of Sample 2. (**a**) Occurrence of cavities and clusters of undispersed nanofiller on the surface.; (**b**) Surface in the end of machining.; (**c**) Changed nature of the chip's formation.

### 3.3 Sample 3 – 4 wt.%

During the machining of Sample 3, the tool also experienced the steepest increase in wear magnitude during the first milling cycle. Further, the rate of wear increase slowed down over the machining cycles and a steady increase in tool wear continued. A very slight increase in $R_a$ parameters was observed in the machining of this sample. Specimen 3 was made without observable cavities, nanofiller clusters, or other undesirable structures that would contribute excessively to tool wear. In **Figure 6a** and **6b**, the difference between the visibility of the toolpaths after the first and last machining cycle can be observed. Due to the addition of 4 wt.% $SiO_2$, the resulting chips are regular flake shaped. These chips are close to 200 μm in size. As with the previous sample, the chips were strongly influenced by the gradual increase in tool wear and their character gradually changed from flake-like (**Figure 6c**) to crumbly again.

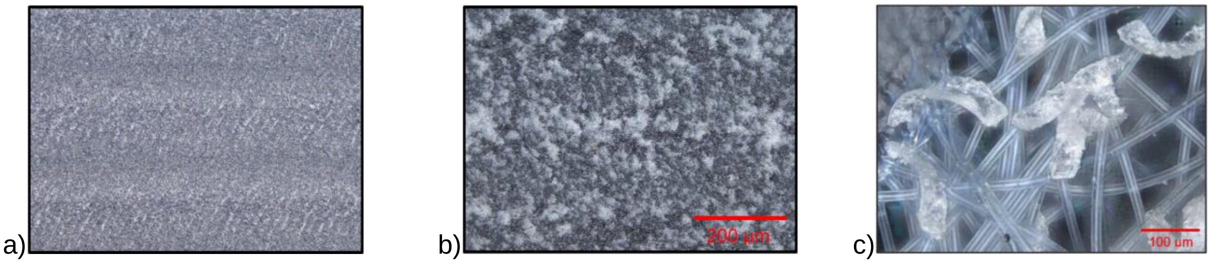



**Figure 6** Overall overview of Sample 3. (**a**) Surface of Sample 3 after 5 minutes of milling.; (**b**) Surface of Sample 3 after 30 minutes of milling.; (**c**) Flake character of chips of Sample 3.

### 3.4 Sample 4 – 6 wt.%

For Sample 4, most of the wear can be observed to occur within the first 5 minutes of machining. In the case of this sample with 6 wt.% $SiO_2$, this represents the formation of approximately 64 % of the final measured $V_B$ size. The rest of the graph shows a slightly increasing trend (**Figure 2**). For this sample, it is possible to observe regularly increasing values of roughness $R_a$ (**Figure 3**). In **Figure 7a,** many white regions representing non-dispersed clusters of nanofiller revealed by the 4th machining cycle can be observed. The size of said clumps relative to the toolpaths can be observed in **Figure 7b**. These randomly distributed clusters contribute significantly to the increase in the magnitude of the $V_B$ wear and the magnitude of the roughness parameters. As the amount of nanofiller increases in the sample structure, it is evident that the filler contributes significantly to the friability of the chip. In **Figure 7c**, it can be observed that even though the chips are flake shaped, there are areas around and between the chips that are crumbly in nature. As the tool wears, the chips change from a flake shape to an almost completely friable shape, forming very small particles.

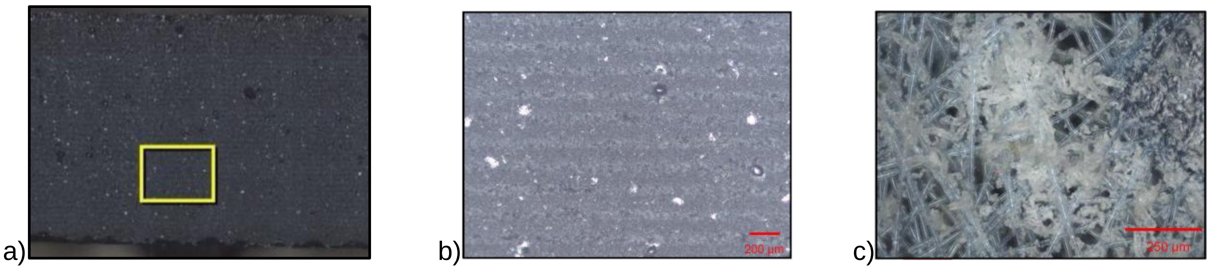



**Figure 7** Overall overview of Sample 4. (**a**) Macro view at machined surface-yellow rectangle represents area of interest.; (**b**) Detail view at the surface structure with clusters.; (**c**) Flake shaped with higher number of areas with crumbly shaped nanocomposite chips.

### 3.5 Sample 5 – 8 wt.%

The tool wear during machining of sample 5 shows different characteristics. During the first cycle there is more wear, as with the other samples, then this trend stabilizes after the next cycle. This is followed by a very gradual increase in the magnitude of $V_B$ until the 4th cycle. During the last two cycles, however, the wear increases rapidly to almost three times the measured value after the first five minutes of machining. This sample shows an atypical trend in the dependence of the roughness parameters. The parameter $R_a$ does not show the expected gradual increase. The increase of the observed roughness parameter shows a linear character until the sudden decrease caused by possible surface homogenisation after the removal of surface defects (**Figure 3**). Cavities of considerable size appear on the surface (**Figure 8a)**, often extending across the entire width of the tool. These cavities interrupt the smoothness of the tool stroke and cause unwanted additional stress on the tool. Furthermore, it is possible to observe the difference in surface quality achieved by the experiment (**Figure 8a** and **8b**). Due to the greater amount of impurity in the sample, there was more tool wear, which is evident in the comparison between the 1st and 6th milling cycle (**Figure 2**). At the end of machining, toolpaths are not discernible on the sample surface (**Figure 8b**). Here, already after the first milling cycle, a relatively large representation of crumbly chips can be observed, which in the previous samples was only visible at the end of the experiment. The chips after the last machining cycle show primarily a crumbly chip character with very fine particles (**Figure 8c**).

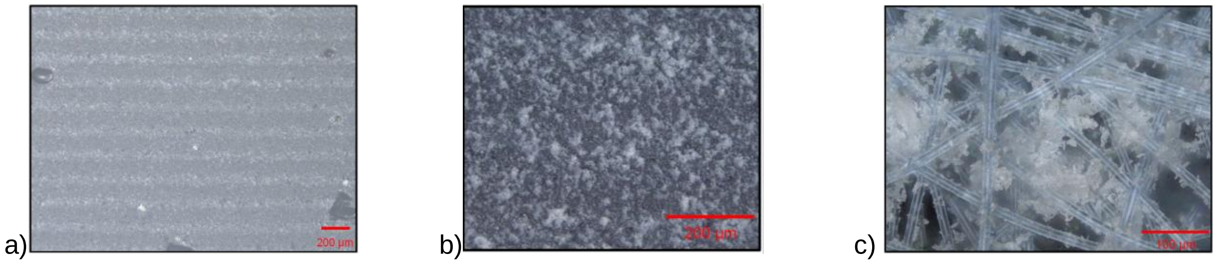



**Figure 8** Overall overview of Sample 5. (**a**) Surface structure with cavities across toolpaths.; (**b**) Quality of finished surface after 30 minutes of milling.; (**c**) Crumbly chips on the fibers of the cloth used for the chips collection.

## 4 CONCLUSION

The trend shows that a higher nanofiller content in the sample structure is associated with a deterioration in surface roughness and associated surface quality. The abrasive nature of the nanofiller increases tool wear and this has an immediate effect on the chip removal mechanism, which in turn affects the quality of the machined surface. This finding must be supplemented by another input factor - the degree of mixing between the nano-reinforcement and the support element, which distorts the assumption of higher wt.% reinforcement = higher tool wear rate. The occurring reinforcement clusters contribute significantly to the influence of tool cut stability and the mechanisms associated with chip formation and resulting surface roughness. The progressive tool wear was already visible after the second machining cycle, where the traces of the chip separation mechanism (visible toolpaths) disappeared. Due to further tool wear, by the end of the experiment, there was almost no chip shearing anymore, but rather ploughing, resulting in a further deterioration of the surface quality. In all the samples examined, the chips were worm-like or flake-shaped at first, but when the chips formed during the last machining cycle were examined, their character always tended towards a crumbly structure with particles smaller than those at the beginning of the experiment.

This study advances knowledge in the field of micromachining of nanocomposite materials. The reason for this study was to assess the effect of wt.% $SiO_2$ on the magnitude of $V_B$ tool wear, $R_a$ roughness and the resulting surface quality. The degree and quality of dispersion of the nanofiller in the matrix appears to be a critical factor for process stability. This is an initial study that will be a starting data set for further research and to expand the knowledge in this area of research.

## ACKNOWLEDGEMENTS

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