Parametric optimization in turning of AA2014/Al₂O₃ nano composite for machinability assessment using sensors

M Prakash, U Mohammed Iqbal*
Department of Mechanical Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai 603203, India.
*Corresponding author: mohammediqbal.u@ktr.srmuniv.ac.in

Abstract. Aluminium metal matrix nano-composites (AMMNC) reinforced with various weight percentages of micro and nano Al₂O₃ particles have outstanding mechanical properties for variety of industrial, aerospace and automotive applications. However, the machinability of AMMNC is still a problem. The presence of abrasive particulates behaves like cutting edge for the tool during machining, resulting in unexpected tool wear, high tool workpiece interface temperature, enormous amount of cutting forces and vibration. In this study, experimental investigations were carried out to assess the machinability in turning of AMMNC under dry condition. A mathematical model was developed to predict the responses, namely surface finish, tool wear, work-tool interface temperature and cutting forces using linear regression analysis. Taguchi based optimization technique has been used to optimize the turning parameters for obtaining the best surface roughness of the components with reduced tool wear, temperature and cutting force. Multiple sensors were used to measure the responses to identify the optimum machining parameters. The frequency domain analysis is carried out to predict the dominant frequency band. Chip morphology analysis is also carried out to assess the machinability. Thus, this work helps to know about the effect of combined micro and nano-particles in the properties of AMMNC and its machinability.

Keywords. Aluminum Metal Matrix Nano Composites, Surface Roughness, Tool Wear, Temperature, Cutting Force, Vibration, Chip Morphology.

1. Introduction
Nowadays the study of metal matrix composites (MMC’s) gained momentum due to their better mechanical properties and is used to replace the conventional materials. Among that aluminum metal matrix composites (AMMC) have huge application especially in medical implant, aerospace components, automobile and electronics instruments. They have outstanding properties such as desired strength to weight ratio, enormous modulus, good ductility, good wear resistance and thermally conductive [1, 2]. In general, AMMC are reinforced with micro/nano size particulates of Al₂O₃, SiC, B₄C, TiC, TiO₂, TiB₂ etc. in to get different desired properties [3-6]. Many researchers reported the various fabrication techniques of aluminum based composites showed consistent improvement in its mechanical properties [7-12]. However, the application of a material not only depend on the fabrication technique but also depends on the subsequent manufacturing processes such as turning, milling, drilling, etc. [13-19]. The problem for machining of Al₂O₃ reinforced AMMC is hard to
machine, because of the presence of abrasive nature of the reinforcement. There are number of studies in machining of MMC. However, only limited attempts were made to investigate the machinability of nano-Al2O3 reinforced aluminum based composites in turning process.

RAO et al., [13] carried out the research on surface roughness while turning particulate composite. It is observed that while machining aluminum fly ash composites the surface roughness decreased as the cutting speeds increase, however it is increased as the feed increases. ROGOV and SIOMAK [14] observed the application of taguchi method for optimizing the machining parameters such as spindle speed, feed rate, depth of cut and tool overhang based on the lower natural frequency and better surface roughness in turning of AA2024 under dry condition with two cutting tools made of AISI 5140 with the different constructions. KILICKAP et al., [15] studied the tool wear (TW) and surface roughness (Rn) in machining of homogenized SiC-p reinforced AMMC in dry turning condition. It was reported that, the TW was increased with increasing cutting speed and mostly observed the abrasion type of tool wear. Rn was also found to be influenced with cutting speed and feed rate. Similar observation is also made by SAID et al. [19] in the machinability study of the AlN-reinforced AMMC using uncoated cemented carbide insert.

The literature review related to machinability assessment using machining temperature, cutting force and vibration are briefly discussed here. ABUKHSHIM et al., [20], observed the heat generation and temperature prediction in high speed machining are the major challenges in machining of composite materials due to practical difficulties to predict them during process. According to KANNAN et al. [21], tool workpiece interface temperature is directly affects the tool life and surface property of the workpiece.

The cutting force components such as torque, drift and feed force are strongly correlated with the TW. It is due to that, the dynamic nature of all these parameters increases the TW gradually with the increasing friction between contacting surfaces. SHOBA et al. [22] studied the influence of machining parameters on the cutting forces in turning of silicon carbide (SiC) and rice husk ash (RHA) reinforced hybrid composites under dry environment. It is observed that cutting forces decrease with the increase in the weight percentage of the reinforcement. It is due to the dislocation densities generated in the composite because of the thermal mismatch between the reinforcement and the matrix.

During machining, the material removal takes place in the form of chip formation which can be of any type, but it can be comprised of the categories of acceptable and non-acceptable. OZCATALEBAS [23] studied the chip formation during machining of AMMC of different volume percentage of in situ Al2C3 particles produced by the mechanical alloying (MA) technique. It is observed that elemental and arc chips are formed during the machining. It is due to the fact that increasing in the hardness with volume fraction of Al2C3 in the matrix. It is also observed that the effect of Al2C3 on the crack formation in shear plane reduce the chip contact length and the chip segment thickness.

In this work, an attempt has been made to fabricate the Aluminium metal matrix nano composite (AMMNC) by considering the AA2014 as a base material and reinforced with micro and nano Al2O3, with various weight percentages using sand casting process. The machinability assessment is made by turning the composite which possesses the best mechanical characteristics under the various weight percentages considered. Multiple sensors such as force dynamometer, IR thermometer, and sound sensor also used to assess the machinability. Frequency domain analysis such as Fast Fourier Transformation (FFT) is also carried out to study the influence of machining parameters in vibration. Chip morphology study is also performed to identify the influence of machining parameters.

2. Material and Specimen Preparation

Aluminium alloy AA2014 was prepared through ball milling using hardened stainless-steel balls of 16 mm diameter. The chemical composition of AA2014 obtained through mechanical alloying is given in Table 1. Al2O3 with a particle size of 20-50 μm and less than 50 nm was used as the reinforcement material. The different weight percentages used are shown in Table 2.
Table 1. Chemical composition of AA2014

| Chemical Composition | Cr | Cu | Fe | Si | Mg | Mn | Ti | Zn | Al |
|----------------------|----|----|----|----|----|----|----|----|----|
| % wt                 | 0.05 | 4.45 | 0.50 | 0.65 | 0.80 | 0.80 | 0.15 | 0.25 | Balance |

Table 2. The weight percentage of MMC

| Matrix | AA2014 |
|--------|--------|
| Al₂O₃  | μm (Wt %) | 0 | 10 | 9 | 8 | 7 | 6 | 5 |
|        | nm (Wt %) | 0 | 0 | 1 | 2 | 3 | 4 | 5 |

Figure 1. Cast Composites before and after turning

Table 3. Mechanical characteristics

| Composition (Micro Al₂O₃ μm + Nano Al₂O₃) | Microhardness (HV) | Compressive strength (MPa) | Yield strength (MPa) | % Elongation | Ultimate tensile strength (MPa) |
|--------------------------------------------|--------------------|----------------------------|---------------------|--------------|-------------------------------|
| AA2014 (100%)                              | 59                 | 140                        | 185                 | 2.67         | 204                           |
| AA2014/10%                                  | 65                 | 157                        | 202                 | 2.87         | 224                           |
| AA2014/9% / 1%                              | 78                 | 168                        | 224                 | 3.09         | 243                           |
| AA2014/8% / 2%                              | 98                 | 327                        | 255                 | 3.33         | 264                           |
| AA2014/7% / 3%                              | 94                 | 225                        | 252                 | 3.15         | 265                           |
| AA2014/6% / 4%                              | 89                 | 178                        | 252                 | 2.67         | 264                           |
| AA2014/5%/ 5%                               | 80                 | 177                        | 252                 | 2.45         | 264                           |

AA2014 is melted in a crucible furnace, and the reinforcements were added and stirred for 20 minutes by alloy steel stirrer. The prepared melt is poured into the preheated sand mold of 150 mm length and 20 mm diameter. Figure 1 shows the castings obtained before and after turning. The fabricated materials were tested for tensile and compressive strength as per the ASTM B557M and ASTM E209 respectively, and the results are shown in Table 3.

It is clearly identified from the Table 3 that AA2014 reinforced with 8 and 2 weight % of micro and nano particles of Al₂O₃ shows significant values regarding compressive and tensile strength than other combinations. This improvement in mechanical properties may be due to the higher stiffness of reinforcement compared to the matrix. Thus the better combination AA2014 (90%) + micro Al₂O₃ (8%) + nano Al₂O₃ (2%) is considered for the machinability study. Figure 2 shows the transmission electron micrograph and its selective area diffraction (SAD) pattern of selected composite. It is observed that nano-Al₂O₃ particles are evenly distributed in the AMMNC.
3. Experimental Setup

The machine tool selected for the present investigation is all geared Unitech 4/2 precision lathe to perform the turning operation with uncoated tungsten carbide turning inserts SNMG 120404-VL, which is mounted using PSKNL 2525M-12 tool holder (Figure 3). Each experiment has been conducted with a fresh cutting edge and total of nine cutting edges has been used as per Taguchi L9 standard OA. Ranges of process machining parameters and their levels are selected and presented in Table 4.
b) Schematic view

**Figure 3.** Experimental setup

### Table 4. Experimental results

| Ex. No | Speed [S] (rpm) | Feed [F] (mm/sec) | DOC [D] (mm) | Ra (µm) | Tool wear (mm) | Temperature (°C) | Cutting Force (N) |
|--------|----------------|------------------|-------------|---------|---------------|----------------|------------------|
| 1      | 1090           | 5.25             | 0.05        | 2.498   | 0.095         | 32.4           | 20               |
| 2      | 1090           | 2.60             | 0.10        | 1.677   | 0.128         | 31.6           | 40               |
| 3      | 1090           | 1.50             | 0.15        | 1.817   | 0.072         | 32.1           | 20               |
| 4      | 740            | 5.25             | 0.15        | 4.481   | 0.077         | 31.9           | 20               |
| 5      | 740            | 2.60             | 0.05        | 1.556   | 0.584         | 31.6           | 60               |
| 6      | 740            | 1.50             | 0.10        | 1.339   | 0.073         | 31.7           | 40               |
| 7      | 486            | 5.25             | 0.10        | 6.35    | 0.979         | 31.7           | 30               |
| 8      | 486            | 2.60             | 0.15        | 2.494   | 0.081         | 31.1           | 90               |
| 9      | 486            | 1.50             | 0.05        | 2.466   | 0.084         | 31.7           | 40               |

The TW is measured at the end of each experiments using video measuring system VMS 2010F. Figure 4 shows the typical tool wear. Chip morphology is also studied using VMS. The surface roughness (Ra) is measured using MITUTOYO SJ-410M surface roughness measuring machine according to ISO 4287 standard, with 0.8 mm of cut off length and 5.6 mm of traverse length. The roughness measurement is made twice at three points, and the average is considered.

In this work, for each machining parametric condition the cutting forces such as feed force (Fx), tangential force (Fy) and radial force (Fz) are measured using lathe tool force dynamometer (Make: Test Master, Model: UIL-15). The component of cutting forces and its direction is shown in Figure 5. The dynamometer is mounted on the tool post as shown in the Figure 3. Cutting forces are measured continuously and force values are taken while machining at the mid length of the workpiece.
Cutting tool temperature at the tool-workpiece interface is measured using EEE TECH IRT-4 infrared thermometer at constant intervals. The vibration signal is acquired with the help of sound sensor in the frequency range 100 – 15000 Hz, impedance 1000 Ohm and sensitivity 5mV/Amps. High pass filter is used to eliminate the noises generated by the environment, and the high frequency sound waves are captured at the sampling rate of 3000 Hz using MATLAB oscilloscope data acquisition system (Figure 3). The frequency domain analysis such as (Fast Fourier Transformation (FFT)) is carried out by using MATLAB ® (R2012a).

4. Results and Discussion

The following section deals with the machinability by turning AMMNC, which was assessed using multiple sensors. The experiments are conducted, based on $L_9$ orthogonal array. The statistical analysis (ANOVA) and regression model has been evolved to obtain the correlations between the machining parameters using MINITAB software at 95% confidence level. The results are presented in Table 5 to Table 8.

The behaviour of output parameters such as TW, $R_a$ and cutting forces with the various machining parameters are discussed here. The machinability is also assessed by correlating with time domain and frequency domain analysis of the acquired vibration signal. Chip morphology study is also carried out to identify the influence of machining parameters.

| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|--------|----|--------|--------------|--------|--------|---------|---------|
| SPEED  | 2  | 0.1202 | 14.47%       | 0.1202 | 0.06009| 0.29    | 0.775   |
| FEED   | 2  | 0.144  | 17.35%       | 0.144  | 0.07202| 0.35    | 0.742   |
| DOC    | 2  | 0.1512 | 18.21%       | 0.1512 | 0.07558| 0.36    | 0.733   |
| Error  | 2  | 0.4149 | 49.97%       | 0.4149 | 0.20746|         |         |
| Total  | 8  | 0.8303 | 100.00%      |        |        |         |         |

Table 6. ANOVA for $R_a$

| Source | DF | Seq SS | Contribution | Adj SS | Adj MS | F-Value | P-Value |
|--------|----|--------|--------------|--------|--------|---------|---------|
| SPEED  | 2  | 5.075  | 23.49%       | 5.075  | 2.5374 | 2.54    | 0.282   |

Figure 4. Typical tool wear measurement

(F$_x$-feed force, F$_y$-tangential force, F$_z$-radial force)
Table 7. ANOVA for work piece and tool temperature

| Source   | DF | Seq SS  | Contribution | Adj SS  | Adj MS  | F-Value | P-Value |
|----------|----|---------|--------------|---------|---------|---------|---------|
| SPEED    | 2  | 0.42889 | 41.15%       | 0.42889 | 0.214444 | 48.25   | 0.02    |
| FEED     | 2  | 0.50889 | 48.83%       | 0.50889 | 0.254444 | 57.25   | 0.017   |
| DOC      | 2  | 0.09556 | 9.17%        | 0.09556 | 0.047778 | 10.75   | 0.085   |
| Error    | 2  | 0.00889 | 0.85%        | 0.00889 | 0.004444 |         |         |
| Total    | 8  | 1.04222 | 100.00%      |         |         |         |         |

Table 8. ANOVA for cutting force

| Source   | DF | Seq SS  | Contribution | Adj SS  | Adj MS  | F-Value | P-Value |
|----------|----|---------|--------------|---------|---------|---------|---------|
| SPEED    | 2  | 736.7   | 24.18%       | 736.7   | 368.34  | 5.72    | 0.149   |
| FEED     | 2  | 1157.8  | 38.00%       | 1157.8  | 578.91  | 8.98    | 0.1     |
| DOC      | 2  | 1023.2  | 33.59%       | 1023.2  | 511.62  | 7.94    | 0.112   |
| Error    | 2  | 128.9   | 4.23%        | 128.9   | 64.45   |         |         |
| Total    | 8  | 3046.6  | 100.00%      |         |         |         |         |

4.1 Tool wear (TW)
Table 4 shows the results of tool wear surface roughness, temperature and the cutting force obtained from the experiments. Figure 6 shows the response of tool wear with various machining parameters of AMMNC. In Figure 6, S1, S2, S3 represents various spindle speeds of 486 rpm, 740 rpm, and 1090 rpm respectively, F1, F2, F3 are various feed rate of 1.50 mm/sec, 2.60 mm/sec and 5.25 mm/sec respectively and D1, D2, D3 are the various depth of cut of 0.05 mm, 0.10 mm and 0.15 mm respectively.

Table 5 is the ANOVA result of tool wear. It is observed that the depth of cut is the most significant factor for the TW, whereas the speed and feed have least significant compared with other machining parameters. From the response plot (Figure 6), it is evident that TW decreases with increasing cutting speed from 486 rpm to 1090 rpm. It is due to the reduced contact time between the tool workpiece interfaces. The main wear pattern is observed to be as regular flank wear (Figure 4). However, crater wear, chipping or fracture of inserts is not observed. It may be due to the segmental chip formation. This is explained in detail in the later section (Section 4.6). However, it is observed that the feed rate increases the TW. It may be due to the abrasion between hard ceramic Al₂O₃ in the matrix and the formation of segmental chip or lose arc chips with increase in feed rate. Hence it is better to increase the speed rather than feed in machining.

4.2 Surface Roughness(Rₐ)
Table 6 is the ANOVA response for Rₐ and the result showed that the feed had significant effect, when compare with speed and depth of cut. The response of Rₐ on machining parameter in turning of AMMNC is shown in Figure 7. From figure 7 it can be seen that the Rₐ increases with increasing feed rates and depth of cut however decrease with increase in cutting speed. The result reveals that the
value of $R_a$ is low at higher cutting speed and high at lower cutting speed. It is due to the fact that at high cutting speed, the machining system becomes stable to generate less vibration and chatter, which leads to produce good surface finish. The reason for this behavior may be due to the presence of hard reinforcement that induces more chatter at low speed in machining of AMMNC.

$R_a$ increases at a slower rate up to a feed rate of 2.60 mm/sec. At higher feed rate of 5.25 mm/sec $R_a$ increases rapidly, it may due to the feed marks on the work, burnishing or honing effect of reinforcement particles [11]. It may also be due to the increase in feed rate which increase the chatter. Detailed study on vibration analysis is discussed in further sections (Section 4.5). A similar observation is also reported during the machining of composites [12-15]. The best $R_a$ can be achieved at the maximum speed of 1090 rpm, low feed rate of 1.5 mm/sec and minimum depth of cut 0.05 mm.

4.3 Work piece and tool interface temperature

Table 7, shows the ANOVA response for work-piece and tool interface temperature. Figure 8 shows the response graph of the work-piece and tool interface temperature with machining parameters. It is observed that there is no significant variation with respect to machining parameters. It is due to the fact that, the thermal conductivity of AMMC is high, so that the workpiece and tool interface heat dissipates quickly and convected away from the machining region. Due to this fact the interface temperature is not shown significant influence in the tool wear. This is also similarly reported by NATARAJ and BALASUBRAMANIAN [17].

4.4 Cutting force

Table 8 shows the ANOVA response for cutting force, and the result showed that the feed had significant effect, when compared with speed and depth of cut. Figure 9 shows the variation of resultant cutting force ($F_r$) with respect to machining parameter in turning of AMMNC. From the Figure 9 it was observed that, resultant cutting force ($F_r$) is reduced with increasing speed. This may be due to the role of dislocation density. In the composite, the dislocation density is generated, which probably due to the coefficient of thermal (CTE) mismatch between the reinforcement and the matrix. While machining of composites the tool passes through these dislocations may be the cause for reduced cutting forces which is also reported by GALLAB et al. [16] i.e. the decreasing trend of cutting force with increase in speed may be attributed due to thermal softening of the work-piece at high cutting speed.

The response of cutting force with respect feed rate is also observed from the Figure 9. It is found that, the resultant force increases with an increase in feed rate. This can be attributed to the increase in the friction between the cutting edge and the work-piece with increase in feed rate, due to the reinforcement.

![Figure 6. Response graph for Tool wear](image1)

![Figure 7. Response graph for surface roughness](image2)
The increase in depth of cut also increases the cutting force. As the depth of cut increases, the contact area between the cutting edge and the workpiece increases, this eventually increases the cutting force. However, the significant observation cannot be made within this parametric study. The cutting force initially increases and then decreases with increase in depth of cut. This kind of non-linearity is mainly because of the formation of built up edge especially at higher depth of cut. From Figure 9 the minimum cutting force is observed for machining of AMMNC at high speed of 1090 rpm, low feed rate of 1.50 mm/sec and at low depth of cut 0.05 mm.

![Figure 8](image1)

**Figure 8.** Response graph for work-piece and tool interface temperature

![Figure 9](image2)

**Figure 9.** Response graph for cutting force (Resultant force ($F_r$)).

![Figure 10](image3)

**Figure 10.** Contribution of machining parameters to responses

Figure 10 shows the contribution of machining parameters to the various responses such as tool wear, surface roughness, work-piece and tool interface temperature and cutting forces. Among the various parameters feed is the most contributing parameter to the responses except depth of cut for the tool wear. The regression coefficient falls within the range of 0.75-0.99 which proved that the ANOVA model is was reasonably accurate. The following regression equation (Equation 1 to equation 4) developed using MINITAB software is to give the relationship between the responses to the machining parameters. It is also used to predict the behavior of dependent variables.
\[ \text{Surface Roughness} = 1.88 - 0.00284 S + 0.735 F + 7.57 D \]  

\[ \text{Tool wear} = 0.544 - 0.000465 S + 0.0752 F - 1.78 D \]  

\[ \text{Work-piece tool interface temperature} = 31.039 + 0.000881 + 0.0757 F - 2.00 D \]  

\[ \text{Resultant Cutting Force} = 43.2 - 0.0362 S + 7.20 F + 109 D \]  

4.5 Vibration signals

In turning process under the normal machining condition, the dominant frequency components in the FFT graph (Figure 11) are around the tool passing frequency, the spindle rotational frequency and their harmonic frequencies. The following Equation 5 and Equation 6 is used to determine the tool passing frequency and natural frequency of the tool holder. For more details refer (ORHAN et al., 2007) [24].

\[ \text{Tool passing frequency (Hz)} = \frac{2\pi \times \text{speed (rpm)}}{60} \]  

\[ \text{Natural frequency} = (k_n l)^2 \sqrt{\frac{E I}{m l^4}} \]

Where \( l \) - the tool holder overhang, \( E \) – Youngs modulus, \( I \) - Moment of inertia tool holder, \( m \) - Mass of the shank.

The FFT analysis of vibration signals were carried out using 1024 data and the FFT spectra with different machining parameters was formed as shown in Figure 11. The vibration resulted by the interaction of tool and work piece has characteristic frequencies with multiples of the tool passing frequency, with the multiplication tool pass number (1-62) as shown in Figure 11.

\[ \text{Figure 11. FFT of vibration signal for the influence of machining parameters} \]

From Figure 11a frequency spectra influence of speed, it is observed that relatively high concentration of energy around the resonant frequency converting wide band width that stretched from 50 Hz to 480 Hz. This bandwidth become dispersed and moving towards lower frequency bandwidth as the cutting speed increases due to the increase in stability at the high cutting speed. It is found that the amplitude of the peak frequency at 50.66 Hz, 120 Hz, 138.66 Hz, 162.66 Hz, 200 Hz, 240 Hz, 280 Hz, 320 Hz, 397 Hz and 477 Hz.
From Figure 11b frequency spectra influence of feed rate, it is observed that with increasing the feed rate the vibration energy being concentrated in the frequency range of (13.3 Hz – 400 Hz). This was attributed to harmonics of the chip formation frequencies.

4.6 Chip morphology
The decrease in the force components and vibration amplitude with the presence of reinforcement was probably due to the increase in the hardness of the hybrid composites. As the reinforcement increases hardness increases. The hardness of the hybrid composites was measured and presented in Table 3. The addition of hard abrasive particles into the matrix changes the deformation behavior of the soft ductile matrix, which results in the chip formation by large plastic shear and which is in good agreement with SHOBA et al. (2015) [22]. Hence the chips formed due to large plastic shear may increase with the increase in the percentage of reinforcement and this could be the possible reason for the decrease in the force components with the increase in reinforcement.

Figure 12 and Figure 13 shows the chip morphology influenced by the speed and feed rate for the constant depth of cut for machining of AMMNC. The discontinuous chip forms are formed due to the presence of hard reinforcement, which act as the chip breaker. As the speed increases the chip become arc chip from loose arc chip.

Figure 12. Chip morphology influenced by varying speed
(Feed 1.5 mm/sec, DOC 0.05mm)

Figure 13 shows the chip morphology influenced by the feed rate, it is observed that with increase in feed rate for machining of AMMC, mostly arc chips are observed. It is due to the formation of micro cracks, which is facilitated by stress concentration around the reinforcement during chip
formation. With increasing the feed rate mostly loose arc chips are observed. This may be due to the reduced chip sticking period, the segment thickness, the tool/chip contact length and increasing chip cutting ratio.

![Chip morphology influenced by varying feed. (Speed 1090 rpm, DOC 0.05mm)](image)

**Figure 13.** Chip morphology influenced by varying feed. (Speed 1090 rpm, DOC 0.05mm)

5. Conclusions

In this work, the fabrication of AA2014 reinforced with micro and nano particles of Al₂O₃ was carried out for different weight percentage. Among the various compositions studied, it is identified that the AA2014 reinforced with 8% (micro) and 2% (nano) Al₂O₃ has better mechanical properties and it is considered for machinability study. Based on L₀ OA the experiments were conducted, and the optimal value is identified as maximum speed (1090 rpm), low feed rate (1.5 mm/sec), and low depth of cut (0.05 mm). Machinability is assessed by relating tool wear, surface roughness and the cutting forces with the machining parameters, with the help of multiple sensors such as temperature sensor, force dynamometer, and sound sensors. Vibration signal were recorded with significant variation with machining parameters. Frequency domain analysis (FFT) of acquired vibration signals and chip morphology studies were also carried out to assess the machinability. The following conclusions are drawn from the above studies

- The flank wear is observed as the main wear pattern for machining of AMMNC. The flank wear decreases with increase in cutting speed. However, with increasing feed tool wear increases enormously.
• The $R_e$ decreases with increasing cutting speed, however increases with increasing feed rate and depth of cut. It is due to the stability and less chatter of machining system at high speed compare with low speed and the feed mark on the work-piece at high feed rate.

• The cutting forces decreases with increasing cutting speed and increases with the feed rate, due to the thermal softening at high cutting speed and increase in friction at higher feed rate. However different trend with depth of cut is observed, due to the dislocation density. This is due to the mismatch of co-efficient of thermal expansion between the matrix and reinforcement. It concluded that the feed has the major contribution in cutting forces rather than cutting speed and depth of cut.

• From the frequency domain analysis, it is concluded that the acquired vibration signal is found to be the best indicator for machinability assessment. The peak frequencies with its energy being concentrated in the frequency range of $(13.3 - 400)$ Hz.

• From the chip morphology analysis, mostly segmented chips are observed due to the presence of reinforcements.

• Thus, this work helps to know about the effect of combined micro and nano-particles in the properties of AMMNC and its machinability. This study also will help the researchers and industries for setting the optimum machining parameters in machining of newly developed materials.

6. References

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