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Machining Characteristics of Multiwall-CNT Reinforced Al/Al-Si Composites using Recurrence Quantification Analysis

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Abstract

Aluminium (Al)/Aluminium alloy composites are emerging as very promising materials, especially in the fields of aerospace and automotive for their various attractive and technically demanding properties. Discontinuously reinforced aluminium metal matrix composites with reinforcements as nanoparticles of ceramics in general and carbon nanotubes in particular have emerged as the forerunner for a variety of general and special engineering and structural applications. In many of the fields where these materials find applications, machining is invariably required for getting correct geometries, dimensions and surface finish of the components. Hence, establishing the machining characteristics of these materials in terms of the deterministic nature of dynamic signals such as cutting force signals and vibration signals is very important and sought after. Machining process has been understood to be nonlinear and chaotic in nature. In this paper a relatively new technique called Recurrence Plots (RP) and Recurrence Quantification Analysis (RQA), a tool to analyse nonlinear and chaotic systems, is used to study the machining characteristics of cast and powder metallurgy Al and Al-Si alloys (LM6 and LM25), CNT reinforced Al/Al-Si composites produced by powder metallurgy route. Cutting force signals were sensed, acquired and analysed using RQA technique. Determinism (DET), which is one of the variables of RQA, indicates the determinism present in a signal. The values of DET were used to compare the machining characteristics. For all the three materials the deterministic nature of the cutting force signal was highest when reinforced with 0.5 weight percentage CNT, followed by respective base alloys produced by powder metallurgy method and casting route.

Keywords: Aluminium; Carbon Nanotube; Determinism; Recurrence Plot; Recurrence Quantification Analysis

1. Introduction

Most of the popular engineering materials are highlighted because of their versatile structural properties. Among the metal matrix composites (MMC) synthesized, aluminium metal matrix composites in general and discontinuously reinforced aluminium metal matrix composites in particular, have emerged as the forerunner for a variety of general and special engineering and structural applications. This trend has been attributed to their superior specific strength and specific stiffness, high temperature capability, lower coefficient of thermal expansion, better wear resistance, improved dimensional stability, and amenability to conventional metal forming techniques [1-4].

Stiffer materials with high damping property are actively sought for dynamic mechanical systems such as in spacecrafts, semiconductor equipments and robotics [5]. Al-Si alloys provide good mechanical properties as well as high damping capacity, particularly for powder metallurgy parts. Discovery of Carbon Nanotubes (CNT) has provided further wings for such applications.

Carbon Nanotube is a nanosize anisotropic material belonging to Fullerene family identified in 1991 by Iijima and has been proved to be very attractive in terms of properties like weight, strength, modulus values and dynamic behaviour. Carbon Nanotubes have been given a great deal of attention because of their unique properties which are leading to many promising applications [6-8]. The mechanical properties reported on carbon nanotubes can be used for developing an entire new class of composite materials. Although most of the research works are focused on the development of nanotube based polymer composites [9] and metal matrix composites using ceramic as reinforcement material [10, 11], attempts have also been made to produce composites using metals such as aluminium [6], lead [12], silver [13], copper [14], magnesium [15] as matrix materials with nanotubes as reinforcement.

Components manufactured by different processes invariably require machining, at least to some extent. Establishing machinability of these newer materials helps the manufacturer to choose machining conditions and component performance. Present work deals with the machining characteristic studies on cast and powder metallurgy Al and Al-Si alloys, CNT reinforced Al/Al-Si composites produced by powder metallurgy route. An attempt has been made to use a relatively new technique called Recurrence Plots (RP) and Recurrence Quantification Analysis (RQA) to study the machining characteristics of these materials.

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2. Recurrence Plots

Recurrence Plots (RP) were first described by Eckmann et al. in 1987 [16]. RP is a technique by which we can qualitatively assess a time series signal embedded in phase space. A recurrence plot can be represented as:

$$R_{i,j} = \Theta(\varepsilon_i - \|x_i - x_j\|) \quad i, j = 1, 2, ... N \qquad (2.1)$$

where xi stands for the point in phase space at which the system is situated at time i, and is a predefined threshold for whose selection there are plenty of criteria. is the norm used to calculate the distances between points in phase space. is the heaviside function. The matrix corresponding to consists of values of only 1 and 0. RP will ultimately be a black and white plot with time on both the axes. A black point in a RP means that the system returns to an -neighbourhood of the corresponding point in phase space [17, 18]. This recurrence gives the name to the method. Figures 1 to 5 demonstrate obtaining RP from time series data.

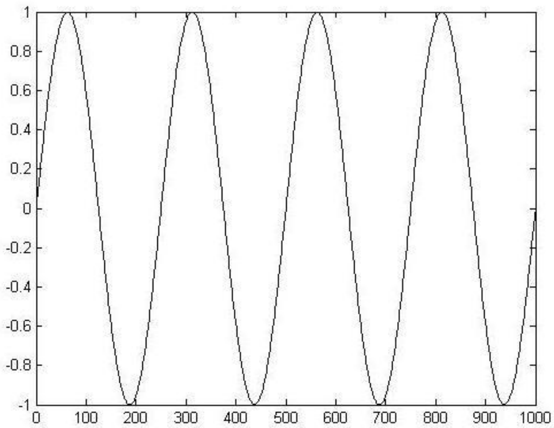


Figure 1: Time domain plot of sine wave (frequency 4 Hz).

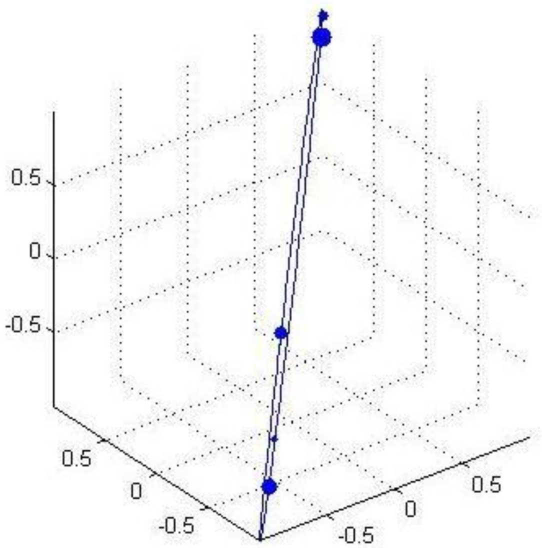


Figure 2: Phase Space plot of sine wave

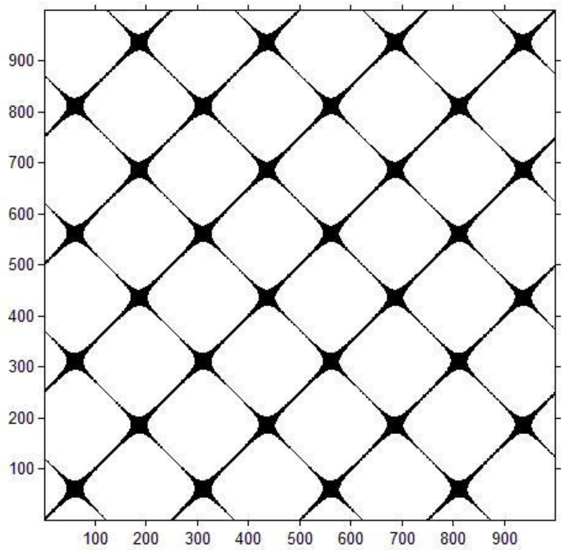


Figure 3: Recurrence Plot of sine wave. m = 2, τ = 2, ε = 0.091 (10 % of mean phase space diameter), Maximum norm.

While figures 1 to 3 have sine wave as the underlying time series, random noise with a standard deviation of 1 is the underlying time series for figures 4 and 5. One can notice easily the difference in RPs of the two cases. While it is the characteristic of deterministic signals to show diagonal lines in RP, homogeneous RP with scattered points will be ehibited by random signals [17, 18, 20]. These are just only two typical type of plots to pick from a large pool of Recurrence Plots. RPs require quite a few criteria and input parameters to be set carefully. The time delay (τ) and embedding dimension (m) required for state space embedding are obtained correspondingly by Mutual Information method [17] and False Nearest Neighbour algorithm [17, 21]. Threshold for the RP in figure 3 was set to be 10 % of the mean phase space diameter [17] whereas that for the RP in figure 5 was 10 % of the maximum phase space diameter, only to get more number of points in the RP. There are numerous criteria to select a proper threshold for a given application [17, 18, 22, 23] even as there lies no fixed single method to select an appropriate threshold.

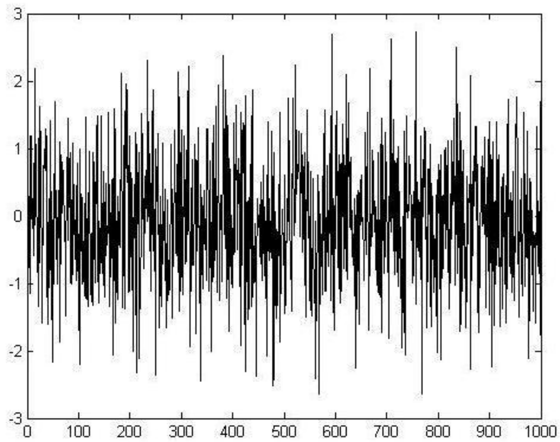


Figure 4: Random noise signal (standard deviation of 1).

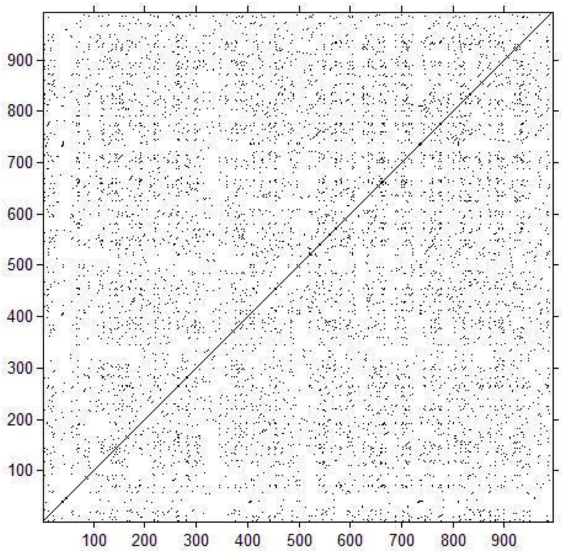


Figure 5: RP of random noise. m = 3, τ = 3, ε = 0.63 (10 % of maximum phase space diameter), Maximum norm.

It is possible to look at RPs and qualitatively assess the dynamics of the uderlying system. However, it demands practice and is not easy always. There are some general guidelines present to interpret the behaviour of a system by observing its corresponding Recurrence Plot [17, 19, 23]. In general, deterministic and regular signals tend to form diagonal line structures whereas random signals form scattered points distributed throughout the RP. Laminar systems (states are changing slowly with time or they are stationary) show vertical line structures in their corresponding RPs.

3. Recurrence Quantification Analysis

It is always difficult to judge the status of a system just by observing the corresponding RP. Some means of quantification of RPs would make understanding the behaviour of the system easy. Charles L. Webber et al. came up with a technique called Recurrence Quantification Analysis in 1992 which was based on quantifying the diagonal line structures present in RPs. In 2002, Norbert Marwan et al. successfully added the quantifications based on vertical line structures. Some of the important variables in RQA are listed below [17].

- Recurrence Rate (RR): Percentage of recurrence points in RP.

$$RR = \frac{1}{N^2}\sum_{i,j=1}^{N} R_{i,j} \qquad (3.1)$$

- Determinism (DET): Percentage of recurrence points which form diagonal lines.

$$DET = \frac{\sum_{l=l\min}^{N} lP(l)}{\sum_{i,j}^{N} R_{i,j}} \qquad (3.2)$$

- Averaged diagonal line length (L): Average length of diagonal lines.

$$L = \frac{\sum_{l=l_{\min}}^{N} lP(l)}{\sum_{l=l_{\min}}^{N} P(l)} \qquad (3.3)$$

- Entropy (ENTR): Shannon entropy of the probability distribution of diagonal line lengths.

$$ENTR = -\sum_{l=l_{\min}}^{N} p(l)\ln p(l) \qquad (3.4)$$

- Laminarity (LAM): Percentage of recurrence points which form vertical lines.

$$LAM = \frac{\sum_{v=v_{\min}}^{N} vP(v)}{\sum_{v=1}^{N} vP(v)} \qquad (3.5)$$

- Trapping Time (TT): Average length of vertical lines.

$$TT = \frac{\sum_{v=v_{\min}}^{N} vP(v)}{\sum_{v=v\min}^{N} P(v)} \qquad (3.6)$$

Table 1 shows the above discussed RQA variables for a sine wave with a frequency of 4 Hz and for a random noise signal. The threshold was set to be equal to 10 % of the mean phase space diameter for both the signals and Maximum norm was used for the calculations. A DET value of 98.66 % for sine wave shows that the signal is deterministic. Since deterministic signals form diagonal lines, all the variables quantifying the diagonal structures (DET, L and ENTR) show higher values for sine wave. Since sine wave is not very agile in behaviour, the variables LAM and TT which quantify vertical structures attain higher values.

Table 1: RQA variables' values for sine wave and random noise (Maximum norm)

Variable/parameter	Sine wave (4 Hz)	Random noise
τ	2	3
m	2	3
ε	0.09	0.14
RR (%)	8.39	0.04
DET (%)	98.66	1.05
L	12.34	2
ENTR	2.56	0
LAM (%)	99.98	0
TT	12.01	0

RP of the noise signal is very scattered as can be seen from figure 5, thus contrasting in nature the RP of a deterministic signal such as sine series which is shown in figure 3 where one gets structured diagonal lines. An interesting comparison can be made between the RQA variables of the sine series and that of the random noise, drawing conclusions about the system dynamics. Very low value of DET for random noise (1.05 % in table 1) confirms that the system has low determinism. This in turn will imply that the plot has no diagonal lines of considerable length. Hence, one gets a lower value of L also in this case. As ENTR is dependent on the probability distribution of diagonal line lengths, it will be lower for noisy signals. In case of random noise, the system is very agile. Hence, the system will hardly be laminar. LAM shows very low values because of this very reason. For the very same reason, TT will also be low for random noise. These variables give a feel of systems' dynamic behaviour. All these behaviours are exactly opposite to that of a deterministic system such as sine wave.

Visual Recurrence Analysis (VRA), CRP Toolbox for Matlab, Dataplore, TISEAN and Bios Analyzer are few of the codes and softwares available for Recurrence Plots and Recurrence Quantification Analysis. For all the RPs and RQA in this work, CRP Toolbox, developed as part of the dissertation work of and by Dr. Norbert Marwan, University of Potsdam, Germany, was used.

4. Work piece Preparation

Commonly available industrial grade cast Al, LM6 and LM25 were procured from the suppliers for preparing work specimen for machining. The powder metallurgy workpieces of Al, LM6 and LM25 and CNT reinforced variants of these materials were prepared in the laboratory using conventional powder metallurgy technique.

4.1. Preparation of Al, LM6 and LM25 by powder metallurgy:

LM6 is a eutectic mixture of Aluminium and Silicon with 11.8 % Si. LM25 is a hypoeutectic alloy with 7 % Si and 0.3 % Mg. Al, LM6 and LM25 powders of 75 micron size were procured from the suppliers and the powders were compacted according to ASTM B 925 03 to form solid billets. These billets were sintered in vacuum furnace at appropriate temperature and time suggested in literatures. The compaction and sintering procedure was verified by measuring the hardness and comparing it with standard values for powder metallurgy materials. The sintered billets were hot extruded at a temperature of 350oC to get the workpieces required for machining.

4.2. Preparation of 0.5 % (weight fraction) CNT reinforced workpieces:

Multiwalled CNT was procured from M/s Sigma Aldrich, Bangalore. Impurities such as graphitic particle, amorphous carbons or any other present in the raw CNT powder were removed by immersing them in concentrated Nitric acid, then filtered and washed with de-ionized water and dried at 120¬ . The Al/Al alloy powders were mixed with CNTs in ethanol solution. These mixed powders were dispersed with mechanical stirring assisted with ultrasonic shaker for 30 minutes. Finally, the mixed powders were dried at 120 in vacuum (less than 10−2 Pa) and ball milled for 10 minutes in Retsch PM100 high energy ball mill. The mixed powders were compacted and sintered into billets and finally extruded into rods at 350 . The specification of the CNT is listed in Table 2.

Table 2: Specifications of the CNT used.

Parameter	Values
Outer diameter	1 to 15 nm
Length	0.1 to 10 μm
Density	2100 kg/m^3

5. Experimental Setup

Figure 6 shows the schematic of experimental setup for the present work. Machining was performed on the workpieces on a Panther 1530/1650 lathe. The machine has a highest attainable spindle speed of 1250 rpm. As indicated in the past research, tungsten carbide tools with better tool life than HSS tools in the machining of eutectic (LM6) and hypoeutectic (LM25) Al-Si alloys [24] has been used. Kennametal DNMG 150608 tool insert was chosen with standard tool holder PCLNR 2020 K12. Cutting forces were sensed using a Kistler 9257 B dynamometer on which the tool post was mounted. The dynamometer in turn was connected to Kisteler 9257 B charge amplifier. The force signals in three directions from the amplifier were acquired by National Instruments PCI-4472 eight channel data acquisition card at a sampling rate of 1000 samples per second with LabVIEW 8.0 being the software interface. Cutting force signals in the cutting direction (Fz) were then taken as the inputs for analysis with CRP toolbox. All the workpieces were of the same size of 8 mm diameter and 80 mm length. The following nine specimens were machined.

- Cast and P/M Al
- 0.5 wt. % CNT reinforced Al composite
- Cast and P/M LM6
- 0.5 wt. % CNT reinforced LM6 composite
- Cast and P/M LM25
- 0.5 wt. % CNT reinforced LM25 composite

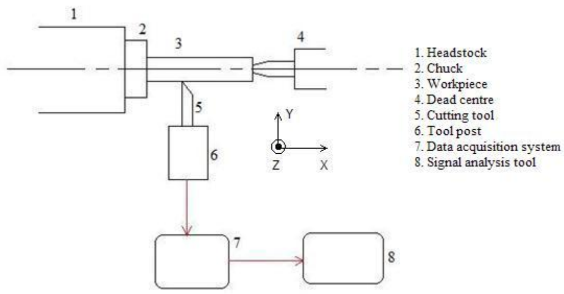
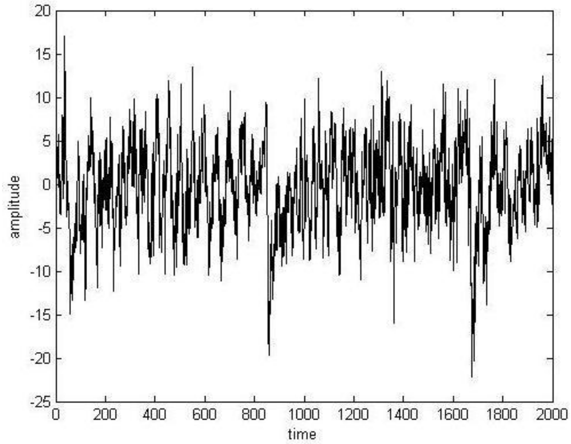


Figure 6: Scheme of experimental setup.

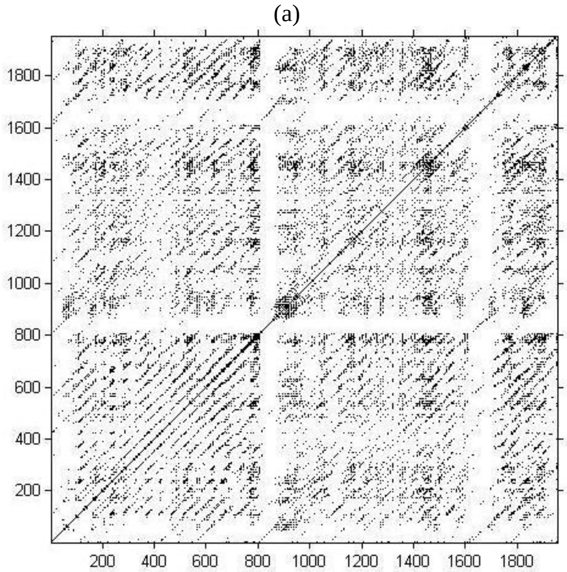
Cutting force signals during machining were sensed and acquired at a sampling rate of 1000 samples per second. For the present work, cutting force signals in the cutting direction (Fz) was considered for analysis. The force signals were the inputs for CRP Toolbox used with Matlab. The criterion to select the threshold was to keep RR at 1 %.

6. Results and Discussions

Turning operation for the materials listed in section 5.0 under the machining conditions of 1250 rpm speed , 0.0375 mm/rev feed and 0.5 mm DOC were carried out and cutting force signal was sensed and acquired to process by RQA technique. The combination of machining parameters was chosen for good surface finish at low MRR. From the RQA, the DET was calculated and used to assess machining characteristics of the materials in view of randomness and the expected value of the variable. The time domain signal and the corresponding RP for LM6 and its variants are given in figures 7, 8 and 9. In all the three plots, recurrence rate (RR) was kept at 10 % so that more recurrence points will be visible in the RPs and hence the line structures are clearly visible.

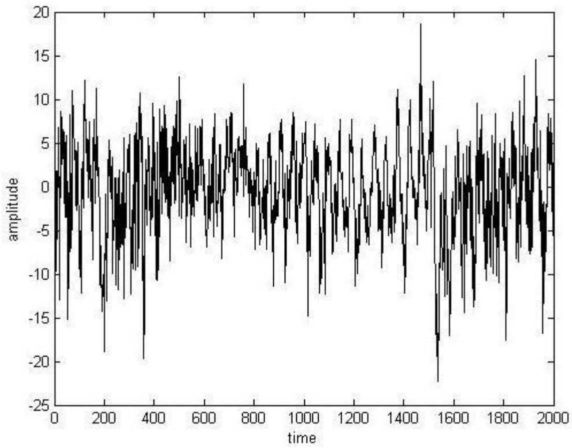


(a)

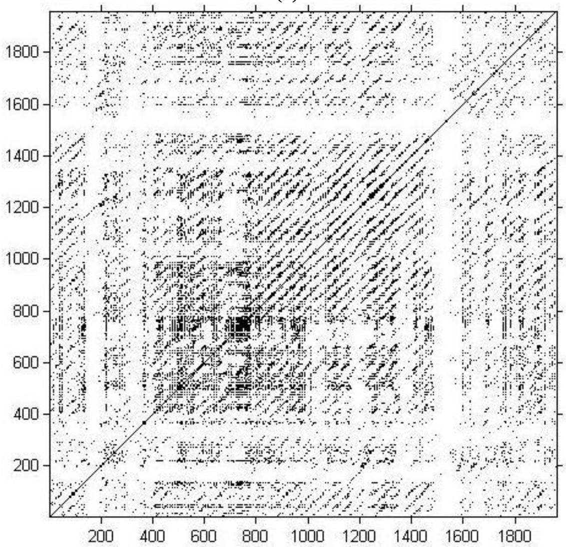


(b)

Figure 8: (a and b): Time domain cutting force signal and corresponding RP for P/M LM6.



(a)



(b)

Figure 9: (a and b): Time domain cutting force signal and corresponding RP for 0.5 % CNT reinforced LM6.

From the RPs for LM6, the amount of diagonal structures are more in case of LM6 produced by powder metallurgy route compared to that produced by casting route. The diagonal structures further improves with reinforcement of 0.5 wt. % CNT in LM6. It indicates that the force signal is more deterministic in case of 0.5 wt. % CNT reinforced LM6 composite. This is a good indication to understand that machining characteristics of powder metallurgy material are better than the cast material. This may be attributed to controlled particle size and uniform distribution of Si as particles which are presumed to act as chip breakers. In addition to this the porosity factor in case of powder metallurgy materils may also aid in breaking the chips. The addition of CNT to LM6 primarily to improve its damping behaviour further improves the deterministic nature of the signal also. This is a good indication that during sintering no reaction has taken place in forming the hard phase Silicon Carbide at the interface and also the CNTs are uniformly dispersed. The CNTs also contribute in improving the deterministic nature of the signal by way of increasing the anti-friction property at the tool-material interface. To quantify the RP, the DET values were calculated and based on the fact that in RQA, dynamic systems giving higher values of DET are considered to be more regular in nature. The DET values for LM6 and its variants are given in Table 3.

Table 3: DET values for LM6 and its variants.

Material	DET (in per cent)
LM6- cast	6.34
LM6- powder metallurgy	17.44
LM6 with 0.5 % CNT	18.67

From Table 3, the value of DET is highest for 0.5 wt. % CNT reinforced LM6 composite produced by powder metallurgy route. This indicates that the machining characteristics of LM6 evaluated in terms of force signal (dynamic in nature) regularity is better for 0.5 wt. % CNT reinforced LM6 composite followed by LM6 produced by powder metallurgy route and LM6 produced by casting route. Similar trends were also observed for Al and LM25. The DET values for Al and its variants and LM25 and its variants are shown in Tables 4 and 5 respectively.

Table 4: DET values for Al and its variants.

Material	DET (in per cent)
Al- cast	11.56
Al- powder metallurgy	21.32
Al with 0.5 % CNT	22.87

Table 5: DET values for LM25 and its variants.

Material	DET (in per cent)
LM25- cast	6.21
LM25- powder metallurgy	11.73
LM25 with 0.5 % CNT	12.61

7. Conclusions

Machining experiments were conducted on Al, LM6 and LM25 produced by casting and powder metallurgy routes. Experiments were also conducted on 0.5 % CNT reinforced composites of the above materials through powder metallurgy route. The following conclusions are drawn from the experimental results. Machining operation is dynamic in nature and RQA technique can be used to assess the machining by determining the regular or random nature of the cutting force signal. For all the three materials, the DET value is highest for the 0.5 wt % CNT reinforced composites produced by powder metallurgy route. The uniformity of particle size, the uniform distribution of Si particles and the anti-friction property of CNT are the factors that makes the cutting force signal more deterministic. To an extent a favourable presence of porosity in terms of shape and size of the pores in powder metallurgy processing contribute towards forming smaller and discontinuous chips. This makes the cutting force signal more deterministic. LM6 having good mechanical properties can be further improvised in terms of its vibration damping ability and stability during machining by reinforcing it with 0.5 wt. % CNT of smaller aspect ratio and processing through P/M route. This material offers excellent scope for manufacturing components for aeronautical, automotive and structural applications.

8. Acknowledgments

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