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Characterization of Chip Morphology for Aluminum Metal Matrix Composites in End Milling Machining

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Abstract End milling using a solid mill cutter is widely used in aerospace, automotive, biomedical, and chemical industries. However, a comprehensive characterization of chip morphology and micro structural and mechanical behavior of machined chips is lacking in the literature. A series of end milling experiments were conducted for studying the chip morphology of Aluminum metal matrix composite. A new multi-view approach to fully characterize metallurgical aspects of chip& chip morphology including top surface and free surface is taken up in this research paper. Each view of the 3-dimensional (3D) chip has been studied for different characteristics. The variation of chip dimensions with cutting parameters was also determined.

Keywords Composites, End Milling, High Speed Camera, Chip Dimensions, Regression Modelling

1. Introduction

The focus of present day is to use materials with low specific weight as it is the best way of reducing the weight of structures. Aluminum alloys are one such example among light weight materials and is used as it has specific characteristics, such as, easy machinability, non corrosive nature and other mechanical and thermal properties. In addition they are relatively easy to shape metals, especially in material removal process such as machining. In fact, aluminum alloys as a class are considered as the family of materials offering the highest level of machinability as compared to other families of lightweight metals such as titanium and magnesium alloys.

This machinability quantifies the machining performance and may be defined for a specific application by various criteria such as tool life, surface finish, chip evacuation, material removal rate and machine tool power. Aluminum alloys are classified under two classes: cast alloys and wrought alloys. Number of criteria are used to classify aluminum, such as, strain-hardenable alloys and heat treatable alloys. Alloys having silicon as the main alloying element involving larger tool rake angles, lower speeds and feeds make them more cost effective to machine. Chip morphology is an important aspect which is mostly used to evaluate the machinability of Al-SiC alloys. Characteristics of chip morphology provides a very useful information in tool design.

1.1. Material used for study

The aluminum metal matrix composites (MMC) are made by mixing the particulate in a molten alloy. The objective of preparing these composites is to make the material tough, stronger, and better machinability. Machining of these composites typically requires the use of diamond cutting tools for efficient production. The properties of MMC materials have been widely examined and found to be light and having good machinability characteristics and hence can replace alloy steels in certain applications. There are various types of aluminum silicon alloy, such as, ADC12 had 10 wt% SiC, 15 wt% SiC and they have been referred to as ADC12-10SiC, ADC12-15SiC respectively. ADC12-10SiC and ADC12-15SiC were also heat treated and were referred to as ADC12-10SiC (HT) and ADC12-15SiC (HT), respectively. Aluminum–silicon alloy (ADC-12) was used as the metal matrix alloy in this paper and chemical composition of ADC12-10SiC is given in Table 1.

Table 1 Chemical composition of ADC12-10SiC

Element	Al	Si	Mn	Mg	Cu	Fe	Ni
Wt %	Base	10.29	0.12	0.47	1.98	0.75	0.8

1.2. Chip Morphology

Chip morphology is an important aspect that is commonly used to evaluate the machinability of Al-SiC alloy. Characteristics of chip morphology can also provide useful information for tool design. By study of chip morphology, researchers have given various important theories like thermodynamic theory of chip formation, stages of saw tooth formation etc.

The comparative survey of chips obtained for the different cutting speeds may help the researchers to identify some of the properties that favor the instantaneous shearing. The mechanism of chip formation at a high speed is different from that obtained in conventional machining. From the past research work, it may be concluded that increase in the cutting speed, at a certain level of speed, the shearing appears for the case of the material. The objective of this research is to determine the speed the change of the chip shape and to understand the phenomenon itself. In addition to introduction in the first section, experimental set up is explained in section-2 and characteristics of chip dimensions and morphology are given in section-3. The analysis of the results are shown and they are discussed in section-4 and conclusions drawn are given in section-5.

2. Experimental Setup

Composite Al-SiC alloy was chosen for experimental studies because of its wide use in both manufacturing industry and research as explained in section-1. A selected combination of input variables, such as, speed, feed and depth of cut are taken for conducting experiments on a vertical milling machine with the coolant on. Solid carbide end mill cutter coated with TiAlN was used for machining. A high speed camera PHOTRON CAM VIEW was used to record the whole process in order to find material removal rate (MRR) and the chips were collected and studied under electron microscope (SEM) to find their length, width, thickness and other micro structural parameters. Three levels of cutting speed ranging from 765 to 1500 rpm, four levels of feed ranges from 31.5 to 120 mm/tooth, and 3 levels of axial depth of cut from 0.5 to 0.7 mm were selected for machining purpose.

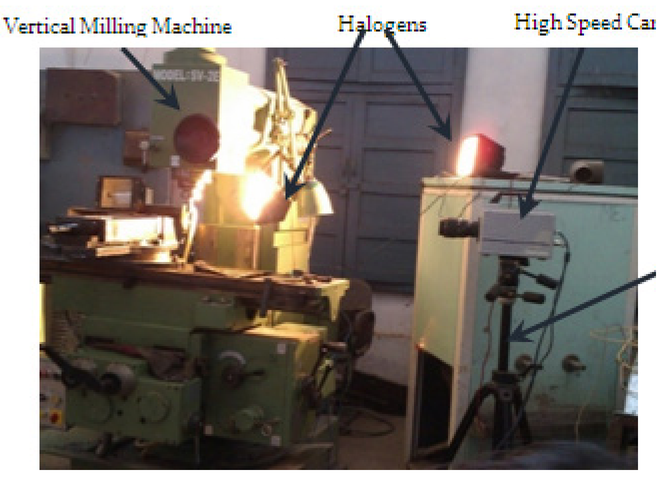

Figure 1. Experimental set up for study of Chip Morphology of AlSiC

The total number of experiments are 36 but design of experiments method is used to select only 8 of them. The detail machining conditions are listed in Table 2 to investigate the effects of process parameters on chip morphology and properties. Machining experiments at each condition were performed three times. The average value is calculated and shown in the table. The corresponding material removal rates were calculated by measuring the dimensions of chips. Experimental setups of all the equipment, viz. high speed camera and scanning electron microscope are described below.

Table 2. Various combinations of input variables

S. No.	Cutting Speed (rpm)	Feed (mm/rev)	Axial DoC (mm)
1	765	31.5	0.7
2	765	50	0.7
3	1070	50	0.5
4	1070	50	0.7
5	1070	78	0.5
6	1070	78	0.7
7	1500	120	0.6
8	1500	120	0.7

2.1. High Speed Camera

It is device used for recording fast moving objects as photographic images onto a storage medium. In the computer there is a specific software for operating this camera. After recording the images stored on the medium, they can be played in back slow motion. This high speed camera can record with a rate from 30 fps to 750000 fps. A problem for high speed cameras is the needed exposure for the film so one needs very bright light hence halogens which impart light on the job were used. Machining is then started and video is recorded for few seconds and chips formed during this time span have been collected and by using this data, MRR has been calculated.

2.2. Scanning Electron Microscope

Images of sample can be produced by using this electron microscope in which beam of electrons are focused on the object. Various signals are produced by using this focused beam of electrons interact with electrons in the sample and detection of information about the sample's surface topography and composition is done. Image is produced by scanning the electron beam in a raster scan pattern and this beam's position is combined with the detected signal to produce an image. A resolution of around 1 nanometer can be achieved with SEM.

3. Characteristics of Chip Dimensions & Chip Morphology

3.1. The Influence of Process Parameters on Chip Dimensions

Since end milling is a 3D cutting process which involves complex geometry of the milling cutter and interactions with the work piece. A basic relationship between tool and work piece interactions during end milling will improve the fundamental understanding on chip formation. However, only simple 2D geometrical relationship between speed, feed and chip length, chip width have been studied.

A 3D view of chip formation during a milling process is necessary to identify the specific cutting actions by different cutting edges. The 3D view is also vital for understanding the formation of a machined surface and subsequent surface integrity. By analyzing the end milling process, a 3D view of chip formation has been established to highlight the dimensions of a milled chip, specific functions of the side cutting edge and end cutting edge, and the relationship with the process parameters such as axial and radial depth-of-cut (DoC). Since machining experiments at each condition were performed three times, the error bars were obtained from measuring different chips by the repeated experiments, i.e., the test repetition variation.

3.1.1. Chip Length

Chip length indicates the time of contact per tooth which is very important for machining. A comparatively long contact time will contribute to tool wear via abrasion and diffusion which will further affect tool life. The influence of milling parameters on chip length reflects the characteristics of contact between the tool and the chip and further affects tool wear/life directly. The variation of chip length at different cutting speeds and feeds (with other parameters constant) are shown in Fig. 2(a-d). The slight decrease in average chip length at the highest feed may be due to the large variation of measures as a result of irregular chip morphology. Length of chips for different combinations of speed, feed and depth of cut are shown in Table 3.

Table 3. Influence of process parameter on chip length

S. No.	Cutting Speed (rpm)	Feed (mm/rev)	Axial DoC (mm)	Length (mm)
1	765	31.5	0.7	5.06
2	765	50	0.7	5.75
3	1070	50	0.5	5.82
4	1070	50	0.7	8.06
5	1070	78	0.5	5.55
6	1070	78	0.7	4.35
7	1500	120	0.6	9.44
8	1500	120	0.7	9.10

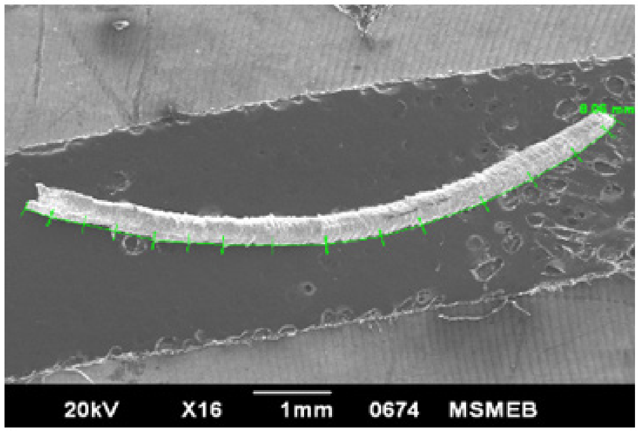

Figure 2(a)
Length = 8.06

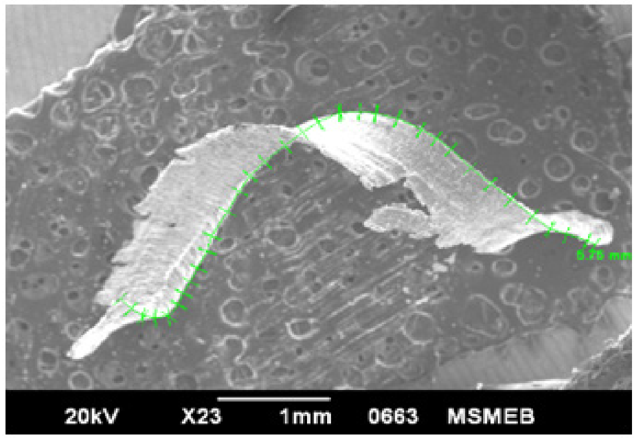

Figure. 2(b)
Length = 5.75 mm

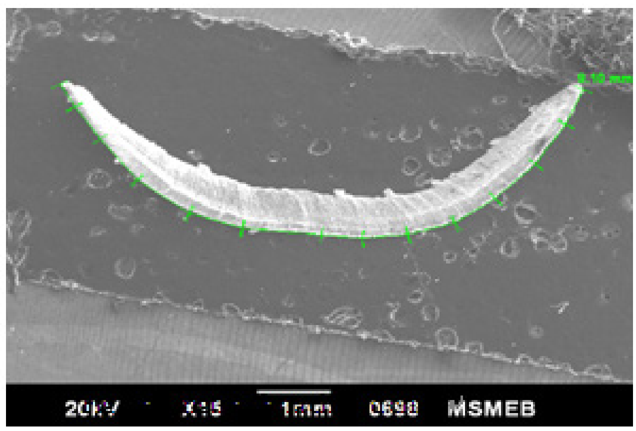

Figure.2(c)
Length = 9.10

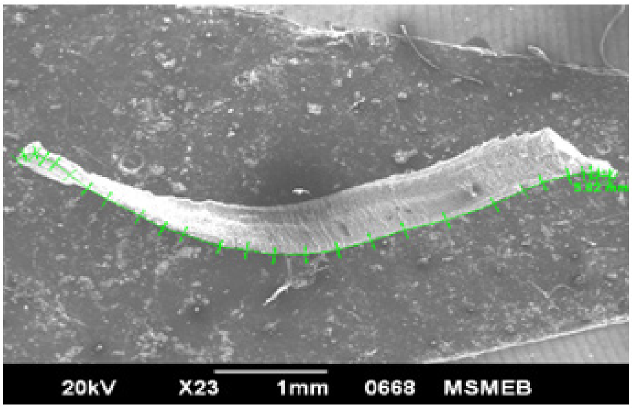

Figure. 2(d)
Length = 5.82 mm

Figure 2. Length of machined chips

3.1.2. Chip Width

Chip width together with chip length largely determines the contact area of the cutting tool/chip. Contact area directly affects tool temperature, wear and the tool life. The variation of chip width at different cutting speeds and feeds (with other parameters constant) are shown in Fig. 3(a-d). The radial depth of cut has a very slight influence on chip length and width.

Table 4. Influence of process parameter on chip width

S. No.	Cutting Speed (rpm)	Feed (mm/rev)	Axial DoC (mm)	Width (mm)
1	765	31.5	0.7	0.845
2	765	50	0.7	0.752
3	1070	50	0.5	0.591
4	1070	50	0.7	0.417
5	1070	78	0.5	0.594
6	1070	78	0.7	0.732
7	1500	120	0.6	0.634
8	1500	120	0.7	0.635

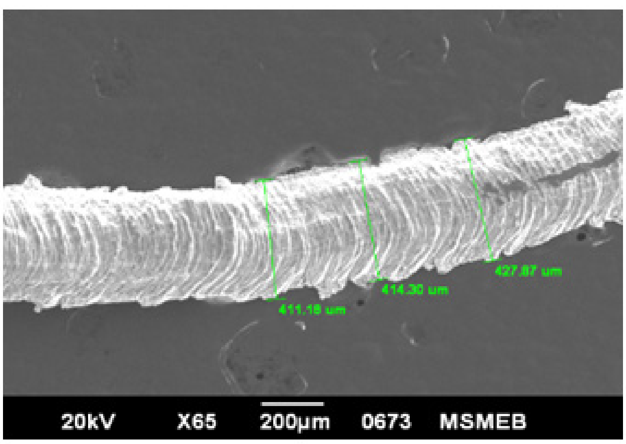

Figure.3(a)
Width = 0.417 mm

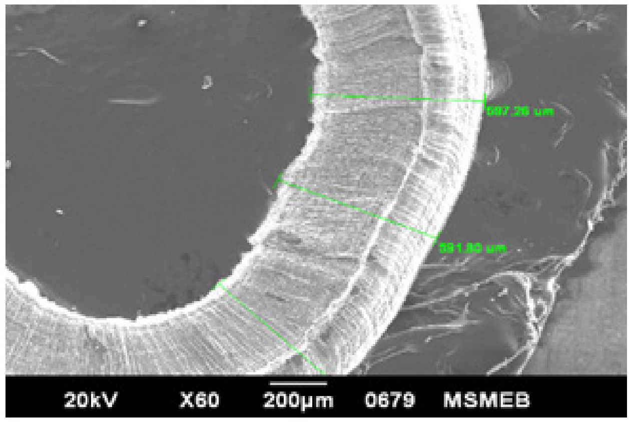

Figure 3(b)
Width = 0.594 mm

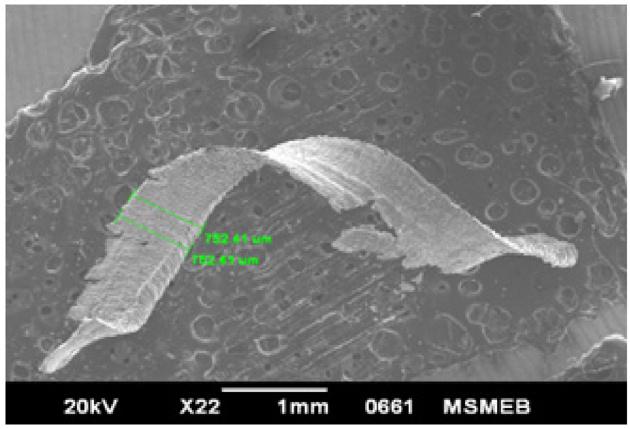

Figure. 3(c)
Width = 0.752 mm

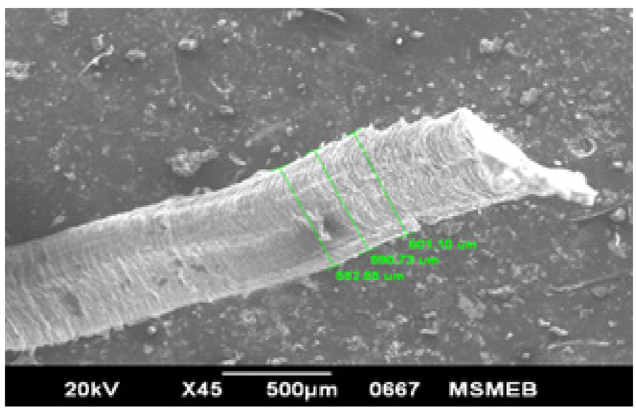

Figure. 3(d)
Width = 0.591 mm

Figure 3. Width of machined chips

However, it affects chip thickness. However, the curled and saw-tooth shaped chip end makes the thickness measurement very unreliable. So the influence of radial depth of cut was not included. Width of chips for different combinations of speed, feed and depth of cut are shown in Table 4.

3.2. Characteristics of Chip Morphology

A multi-view approach is used in this research work to fully characterize chip morphology: top surface, free surface, back surface (tool/chip contact surface), and the cross-section surface. The different characteristics of each surface were detailed as follows.

3.2.1.Top Surface

The SEM images of top view of the machined chips at different cutting speeds are recorded. The characteristics of saw-tooth can be observed from top surface. This view has been used by the majority of machining researchers. It was observed that many segmentations or saw-tooth occur but are irregular and small at relatively low cutting speeds. When the cutting speed increases, saw-tooth frequency decreases.

This phenomenon become more obvious when the saw-tooth width which is defined as distance between neighboring peaks and height which is defined as peak-to-valley distance become larger with increase in cutting speeds. This indicates that the width is less at low cutting speeds. However if the cutting speed is increased, machining instability happens due to larger saw teeth phenomenon which could be one important reason for chattering in high-speed milling Al-SiC. Values corresponding to all the combinations are given in Table 5.

Table 5 Influence of process parameter on shear band

S. No.	Cutting Speed (rpm)	Feed (mm/rev)	Axial DoC (mm)	Shear Band (μm)
1	765	31.5	0.7	52.76
2	765	50	0.7	48.006
3	1070	50	0.5	50.2
4	1070	50	0.7	116.99
5	1070	78	0.5	57.18
6	1070	78	0.7	43.16
7	1500	120	0.6	87.02
8	1500	120	0.7	32.2

3.2.2. Free Surface

The views of free surface at different cutting speeds are shown in Fig. 4. It can be seen that the free surfaces possess Lamella Structures. Lamella structures are composed of very fine, alternating layers of different materials in the form of lamellae. The lamella structures in the major section incline due to the shearing by the side cutting edge, while the lamella structures in the corner section is vertical due to the influence of the nose radius of the corner cutting edge.

Within the same measurement distance, the number of the lamella structures is different in different sections on the free surface. The number of lamella structures is also different at different cutting speeds. The difference in lamella number within same measuring range in different section and at different cutting speeds is quite considerable.

With the increase in cutting speed, the lamella number decreases. However, the lamella becomes clearer, which means the height and width of the saw-tooth become larger. The frequency of saw tooth in the corner section is much higher than that in the major section, which means the cutting mechanism are different for the two cutting edges. The material in the corner section becomes thinner compared with the major section due to the nose radius of the corner cutting edge. It suggests that cutting thin material tends to produce saw-tooth chips of high frequency.

4. Analysis

4.1. Variation in Chip Length

Figure 5(a) shows the variation of length of chip with cutting speed and it can be seen that the chip length increases with the increase in cutting speed. This may be contributed by the material softening induced deformation resulted from high cutting temperatures due to the increase in cutting speeds.

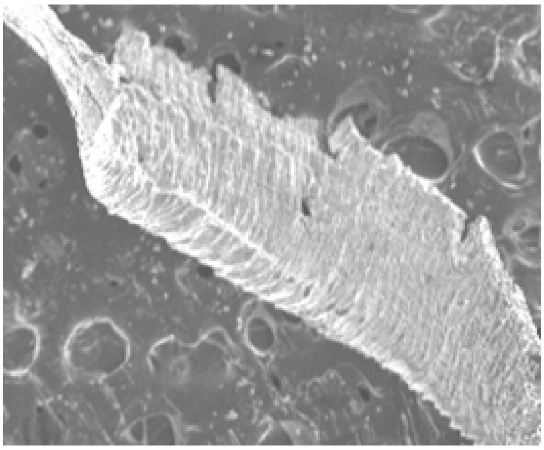

Figure. 4(a)

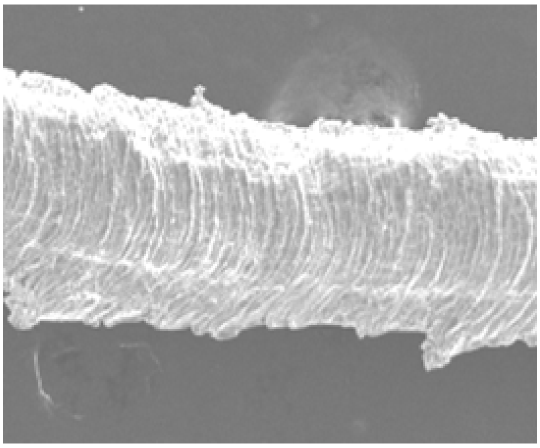

Figure. 4(b)

Figure 4. Lamella structures at different cutting speeds

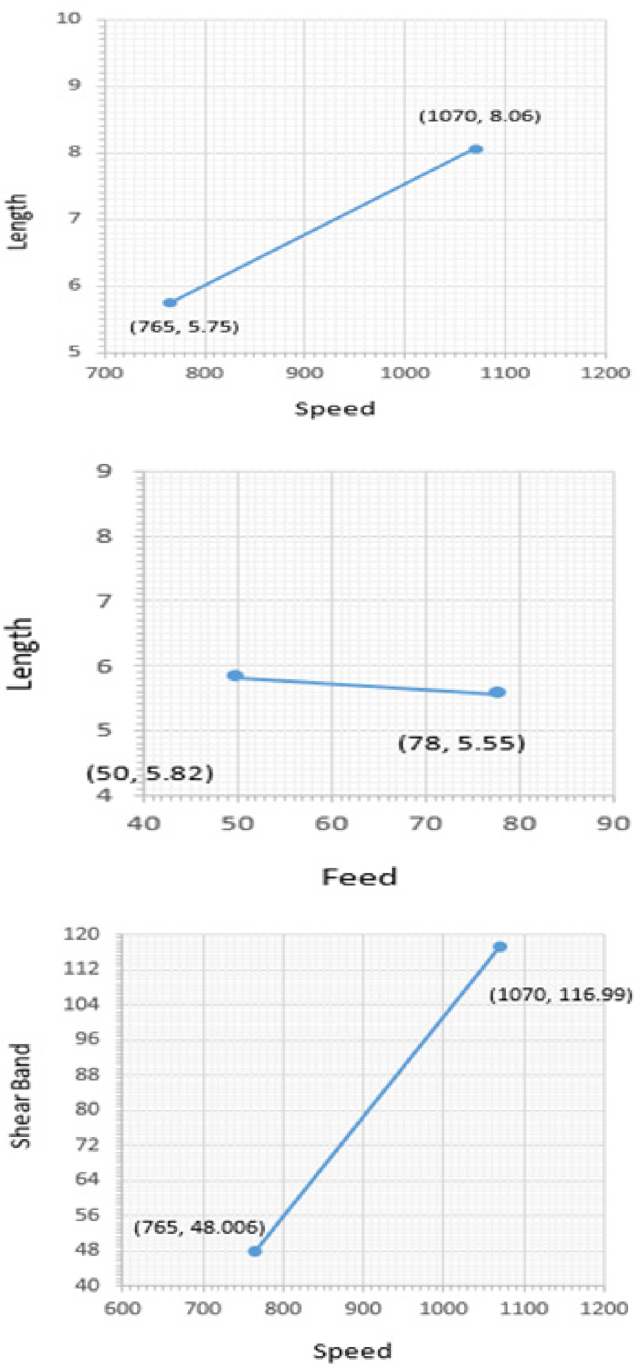

Figure 5. Variation in chip length

Fig. 5(b) shows that chip length also increases with the increased feed. This is expected since the increased feed increases the cutting length.

4.2. Variation in Chip Width

Chip width decreases with the increased cutting speeds. The chip length is increased with increase in speed and feed, therefore the constant of chip volume yields a shorter chip width as shown in Fig. 6(a). Fig. 6(b) shows that chip width also decreases with the feed. Since chip length in Fig. 5(b) increases with feed with the constant speed and depth of cut, so the chip width becomes shorter on increasing feed due to change in constant volume.

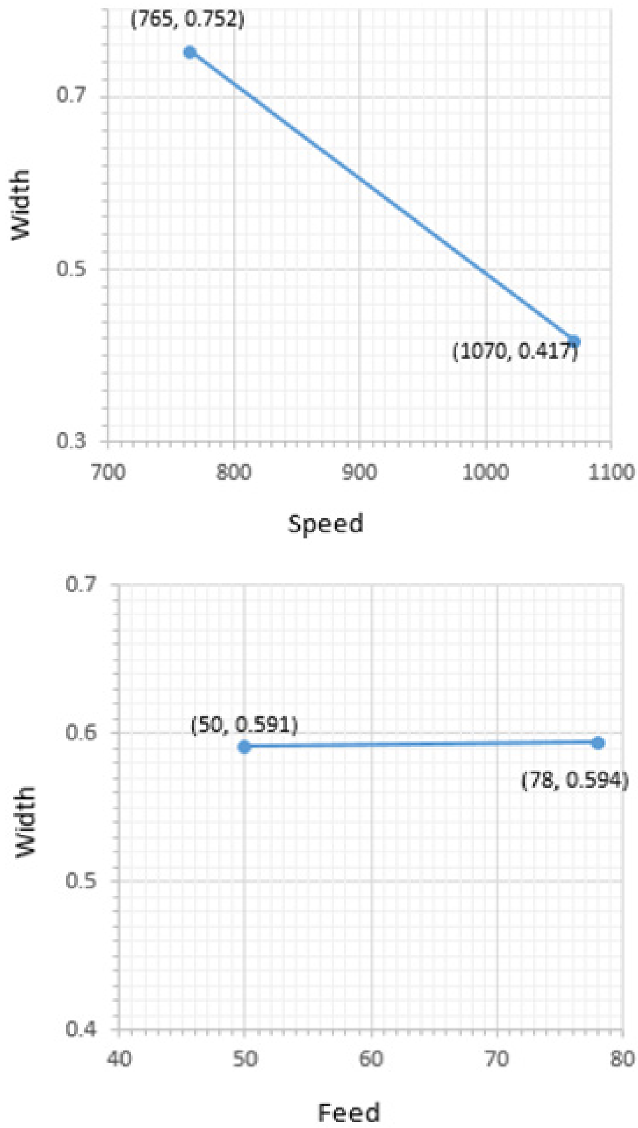

Figure 6. Variation in Chip width

Table 6. Influence of process parameter on length, width and thickness

S. No.	Cutting Speed (rpm)	Feed (mm/ rev)	Axial Doc (mm)	Length (mm)	Width (mm)	Thickness (mm)	MRR (mm^3/s)
1	765	31.5	0.7	5.06	0.845	0.001	0.0183
2	765	50	0.7	5.75	0.752	0.057	0.5923
3	1070	50	0.5	5.82	0.591	0.031	0.2771
4	1070	50	0.7	8.06	0.417	0.054	0.3845
5	1070	78	0.5	5.55	0.594	0.019	0.1367
6	1070	78	0.7	4.35	0.732	0.041	0.2933
7	1500	120	0.6	9.44	0.634	0.025	0.3034
8	1500	120	0.7	9.10	0.635	0.036	0.3910

4.3. Variation in Shear Band

Shear band is the most important characteristic of the milled chips and its magnified view is shown in Fig. 7. Shear bands have been observed at all the milling conditions that were studied. With increase in the cutting speed, shear bands become larger and wider as they are generated by side cutting edge. The large deformation of phase can be seen in the shear bands. Due to the large deformation, the β phase in the shear bands becomes extremely thin. However, no cracks were observed throughout the phases in the shear bands.

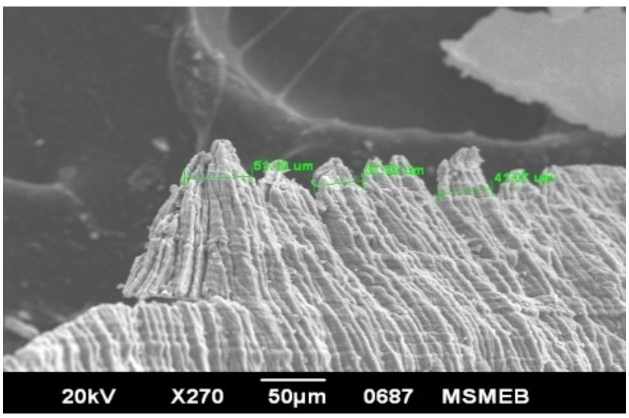

Figure 7. Variation of shear band with speed

4.4. Regression Analysis

Regression Analysis is used in this paper to study the relationships among variables. The dependent variable is taken as material removal rate (MRR) and the independent variables are speed, feed and depth of cut. Minitab 15 software is used for regression analysis.

It may be concluded that the speed of transition exists beyond which the chip shows bands localizing the stress together with saw-tooth chip type with a metallurgical change. From a local increase of deformation due to a defect in the structure, there is a local increase of the work piece temperature due to the plastic work. If the time of loading is short, the increase of temperature thus created decreases the flow stress of the work material by thermal softening. That's what favors again the deformation; the separation by adiabatic shearing and the evacuation of the chip.

5. Results

Final results obtained from this project are shown in Table 6 which includes values of chip length, chip width, chip thickness and MRR on all the eight combinations-

5.1. Micro Hardness Variation

Micro hardness measurements were performed on the top surface and cross-section surface. Four measurements across chip thickness are made on the top surface and one across shear band. Similarly, five rows of measurement were conducted across the thickness on the major sectional surface and corner sectional surface. In addition to these, six measurements are taken for hardness on the top surface in order to compare the results.

5.1.1. Micro Hardness Variation on the Top Surface

From the analysis of micro hardness it was seen that at the very top surface, the micro hardness is higher than that in the immediate subsurface, while the micro hardness is relatively stable in the bulk chip. The higher hardness on the top surface may be due to the quenching effect by the surrounding air. In milling operation, a large fraction of deformation induced cutting temperatures are conducted into the bulk chip. The conducted cutting temperatures anneal the immediate subsurface materials due to the relatively low heat conductivity of ADC12-10SiC. The annealing phenomenon leads to the reduced micro hardness. Another possible reason for the reduced micro hardness may be due to the edge effect in micro hardness measurement since the measurement location is very close to the chip edge. Surface oxidation may be a contributing factor for the increased micro hardness on the surface, but this remains an open question for future study.

5.1.2. Micro Hardness Variation on the Cross-Section Surface

In the major section, the hardness variation is similar to that on the top surface. The underlying mechanisms for hardness variation should be same. This may be due to more shear induced strain hardening by the tool nose radius. As a matter of fact, the lamella structures do have more frequency than in the major section. It means the materials in the corner section experience more shearing.

5.2. Regression Relationship

Result obtained from regression analysis is as follows:

Regression Analysis is done by taking MRR (in columnC4) as dependent variable and cutting speed, feed and depth of cut (in columns C1, C2 and C3) as independent variables).

The regression equation is

C4 = - 0.119 - 0.000101 C1 + 0.00182 C2 + 0.624 C3

Where,

C1 = Speed of cutter (rpm)
C2 = feed (mm/rev)
C3 = depth of cut (mm)
C4 = MRR (mm^3/sec) The MRR is inversely proportional to cutting speed and directly proportional to feed and depth of cut.

6. Conclusions

A series of end milling experiments of Al-SiC were conducted to characterize 3D chip morphology and study the micro structural and mechanical behavior of machined chips. The major findings may be summarized as follows-

- An innovative multi-view approach has been provided to fully characterize 3D chip morphology: top surface, free surface, back surface, and cross-section surface.
- The top surface is characterized by saw-tooth segmentation which increases by the cutting speed, while the saw-tooth frequency reduces with the cutting speed.
- The free surface has two distinct sections by the side and corner cutting edge, respectively. The major section shows less lamella structure but the corner section has more lamella structure.
- Chip length increases with cutting speeds and feeds increases, while chip width decreases with the cutting speeds and feeds.
- The regression equation shows inverse proportionality between MRR and cutting speed and is in agreement with the earlier research works.

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