Internal Friction and Compressive Deformation in the Primary Zone during the High-Speed Cutting of SiCp/Al Composites

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Internal friction and compressive deformation in the primary zone during the high-speed cutting of SiCp/Al composites

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Abstract

The present work proposes that there is internal friction and compressive deformation in the primary zone. Mathematical model was established, in which the internal friction coefficient and some compressive characteristics of serrated chips were calculated. High-speed orthogonal cutting experiment was performed on SiCp/Al composites at cutting speeds of 10–350 m/min and feed rates of 0.07–0.12 mm/r. The internal friction and compressive deformation in the primary zone were investigated by combining results obtained in the experiments with the mathematical model. The internal friction coefficient (0.21–0.47), compressive stress (185.4 MPa–226.9 MPa), and compressive strain rate (0.013×10^4 /s– 0.554×10^4 /s) increased with increasing cutting speed. However, the compression value (17.3 μ m–50.0 μ m) and compressive strain (0.18–0.26) decreased with the cutting speed.

Keywords: Internal friction; Compressive deformation; SiCp/Al composites; High-speed cutting

Nomenclature			
a_c	Depth of cutting (mm)	F_T	Thrust force (N)
a_w	Width of cutting (mm)	F_s	Shear force (N)
L_{AB}	Shear plane length (mm)	N_s	Compression force (N)
ΔX	Actual slip distance (μm)	F_f	Friction force (N)
ΔZ	Theoretical slip distance (μm)	Δt	Unit cutting time (s)
$\Delta Z - \Delta X$	Compressive value (μm)	α_0	Relief angle ($^\circ$)
H_1	Serrated chip root thickness (μm)	ϕ	Shear angle ($^\circ$)
H_2	Serrated chip top thickness (μm)	γ_0	Rake angle ($^\circ$)
V	Cutting speed (m/min)	σ_s	Compressive stress (MPa)
V_c	Chip outflow speed (m/min)	ε_s	Compressive strain rate (s^{-1})
V_s	Shear slip speed (m/min)	μ_{in}	Internal friction coefficient
f	Feed rate (mm/r)	τ_s	Shear stress (MPa)
F_c	Cutting force (N)	ε_s	Compressive strain

1. Introduction

Recently, metal matrix composites (MMCs) have received increasing attention from academia and industry. Among these MMCs, silicon carbide-reinforced aluminum matrix (SiCp/Al) composites are considered especially promising materials due to their superior properties compared with those of conventional materials. These composites are characterized by good dimensional stability, lower coefficients of thermal expansion, high specific strength[1–2] and good wear resistance which can increase with the rising volume fraction of SiC particles[3]. High dislocation density[4], crystalline refinement and load transfer[5] are the main strengthening mechanisms of SiCp/Al composites. These materials are widely used in (for example) aerospace components, advanced weapons, optical components, automotive manufacturing, precision instruments, and electronics [1,6–9]. In addition, SiCp/Al composites will produce serrated chips during the cutting process, which lead to high-frequency fluctuations of the cutting force, and exacerbate the wear and damage of the tool. Therefore, machining of SiCp/Al composites is extremely difficult[10], and results in severe tool wear as well as poor tool durability and surface integrity [11–13].

Friction phenomena within the tool–chip interface has been well investigated [14–16]. Behera et al.[16] proposed dual contact zone theory (sticking-sliding) instead of single contact zone theory to model the chip-tool contact relation. Frictional forces has been put forward to consist of sliding friction and rolling friction [17]. Smolenicki et al.[18]developed a newly in-process tribometer for quick characterization of friction coefficient in orthogonal cutting. Grzesik et al. [19] proposed a new friction model for the oblique cutting, extending the simple Merchant's model by taking the influence of tool wear into consideration. Nair et al.[20] determined the effects of the tribological behavior of SiC particles on billet deformation characteristics. The effect of applied pressure on the tribological behavior of SiCp reinforced aluminum alloy has been investigated[21]. Xu et al. [22] proposed the

shear slip distance and established a high-speed orthogonal model of shear slip deformation which can be used to calculate the important parameters of chip formation. The cutting force prediction in machining of MMCs was also investigated [17,23-24].

Two main theories for serrated chip formation mechanism are widely investigated: period brittle fracture [25] and adiabatic shear theory [26]. Duan et al. [27] divided the deformation process of the shear zone into four stages, namely the: occurrence of shear localization, generation of shear localization, crack initiation, and crack propagation. According to Huang et al. [28], the growth and coalescence of voids and cracks lead to sudden shear fracture on the free surface of chips; as a result, serrated chips are formed via the sliding of material. The formation of serrated chips was also attributed to the deformation and the propagation of a crack in the primary shear zone [29]. Du et al. [30] proposed that the SiCp/Al composites chip-formation mechanism was based on severe plastic deformation of the Al matrix, the contact position between the SiC particles and the diamond grit, and the removal mode of these particles.

Few studies have considered the existence of internal friction in the primary zone. During the cutting process, material undergoes shear slip in the primary zone and there should be relative movement within material. Therefore, the present work proposes there is friction in the primary zone, which is referred to that produced by the slip movement in the shear plane and called internal friction. For serrated chip, shear slip is insufficient to explain actual sawtooth shape independently and pressure should be present during cutting. Therefore, the present work proposes the formation of sawtooth is supposed to be accompanied by compressive deformation, there is compressive deformation in the primary zone. Understanding more about these may provide technical basis for controlling chip serration degree to enhance the surface quality of the workpiece. A mathematical model was developed and high-speed orthogonal cutting experiments of SiCp/Al composites are conducted. Analysis and discussion about internal friction, compressive deformation in primary zone were investigated, enriching the understanding of them.

2. Mathematical model for serrated chip

According to Merchant's theory, the shear angle can be measured from the chip thickness:

$$\phi = \arctan \left[a_c \cos \gamma_0 / (H_1 - a_c \sin \gamma_0) \right] \quad (1)$$

According to the geometric relationship shown in Fig. 1, the shear stress on shear plane AB can be obtained from:

$$\tau_{AB} = F_s / (L_{AB} \times a_w) = \sin \phi (F_c \cos \phi - F_t \sin \phi) / (a_c a_w) \quad (2)$$

Fig. 1. Mathematical model for serrated-chip

The distance between two actual slip lines is referred to as the actual slip distance (considering compressive deformation). Similarly, the distance between two theoretical slip lines (without considering compressive deformation) is referred to as the theoretical slip distance. According to the principle of volume constancy, the area before and after compression is the same, hence:

$$S_{CEMN} = S_{ABCK}$$

$$\Delta Z = \Delta X + (H_2 - H_1) \Delta X / (2H_1) = (H_2 + H_1) \Delta X / (2H_1) \quad (3)$$

The compressive stress can be calculated from:

$$\sigma_s = N_s / (L_{AB} a_w) = \sin \phi (F_c \sin \phi + F_t \cos \phi) / (a_c a_w) \quad (4)$$

The compressive strain can be expressed as follows:

$$\varepsilon_s = (\Delta Z - \Delta X) / \Delta Z = [(H_2 + H_1) \Delta X / 2H_1 - \Delta X] / [(H_2 + H_1) \Delta X / 2H_1] = (H_2 - H_1) / (H_2 + H_1) \quad (5)$$

Set time of the process that initial compressive strain increase from 0 to ε_s as Δt , the compressive strain rate can be written as:

$$\varepsilon_s' = \Delta \varepsilon / \Delta t = (\varepsilon V) / L_{AL} = (\varepsilon V) / (\Delta Z / \sin \phi) = [10(H_2 - H_1)V \cdot H_1 \sin \phi] / [3(H_1 + H_2)^2 \Delta X] \quad (6)$$

The internal friction coefficient in the primary shear zone can be calculated as follows:

$$\mu_{in} = F_f / F_n = (\tau_s \cdot A_\tau) / (\sigma_s \cdot A_\sigma) \text{ and } A_\tau = A_\sigma$$

$$\mu_{in} = \tau_s / \sigma_s \quad (7)$$

The internal friction coefficient and compressive characteristics including the compression value, compressive stress, strain, and strain rate are able to be calculated when the forces and some chip parameters are known. The cutting force and thrust force can be measured by the dynamometer during the experiment. Furthermore, the slip distance and chip thickness can be determined from the scanning electron micrograph of the chip. The further

investigation is in section 4.

3. Experiment and methods

3.1. Material

SiCp/Al (30% volume fraction) composites was used to perform high-speed orthogonal cutting experiments. The SiCp/Al (30p) composite was obtained via stir casting. This composite was machined into workpieces each with a diameter and thickness of 80 mm and 2 mm, respectively. A 12 mm-center-hole, for mounting the workpieces on the three-jaw chuck using custom fixtures, was also machined into the workpieces.

3.2. High-speed orthogonal cutting experiment

The high-speed orthogonal cutting experiment was performed under dry conditions on a DMG-CTX 310 CNC lath, (see Fig. 2 for the experimental setup details). SECO-SCFCL 1212F09 was selected as the tool holder. This holder mounted the cutting tool SECO-CCMW 09T302F-L1 (PCD 20) at 0° rake angle, 0° inclination angle, and 7° relief angle. The cutting force and thrust force were measured by a Kistler 9257B dynamometer. The dynamometer is quartz three-component dynamometer for measuring the three orthogonal components of a force, consisting of four three-component force sensors and can perform multicomponent measurements of forces. A transverse feed, where the feed motion is perpendicular to the spindle axis, was employed. The diameter of the cutting workpiece changed continuously during the feeding process. In order to ensure a constant cutting line speed, the spindle speed was set to constantly vary.

The experimental parameters are listed in Table 1. All the produced chips and records of cutting forces during the experiments were collected and sorted, thereby providing the parameters for the established model.

Fig. 2. Experimental setup details.

Group	Cutting Speed V (m/min)	Feed rate f (mm/rev)	Width of cutting a_w (mm)
1	10, 30, 50, 150, 250, 350	0.07	2
2	10, 30, 50, 150, 250, 350	0.12	2

Table 1. Experimental parameters

3.3. Chip treatment and measurement

Fig. 3. Schematic showing chip measurement.

The chips associated with different cutting conditions were collected and fabricated into samples (after grinding, polishing, and corroding). These samples were then observed with a Merlin field emission scanning electron microscope. As shown in Fig. 3, the actual slip distance and chip thickness values were obtained from the scanning electron micrograph of the chip. The average values for multiple measurements were taken as the final values.

4. Results and discussion

4.1. Basic characteristics

(a)

(b)

Fig. 4. Basic parameters: (a) force, (b) SEM image of chip subjected to 0.07 mm/r and 30 m/min after the experiment, (c), (d) SEM image of chip subjected to 0.12 mm/r and 30 m/min, (e) actual slip distance and (f) chip thickness.

4.1.1. Force

The main cutting force and the thrust force range from 48.6 N to 77.5 N and 37.7 N to 58.8 N, respectively. When the cutting speed increases, the thrust force is relatively stable, whereas the cutting force increases. Both forces increase with increasing feed rate. In the first deformation zone, a relatively high cutting speed can simultaneously induce the strain hardening effect and the thermal softening effect. However, the hardening effect is stronger than the softening effect, thereby resulting in an increasing force.

4.1.2. Chip characteristics

4.1.2.1. Chip features

Fig. 4b shows the microstructure of the SiCp/Al (30p) composites after the experiment, where SiC particles fragment into irregular particles. Moreover, this also shows that the SiC particles have undergone considerable changes during the cutting process and have a significant effect on this process. There is interaction between SiC particles and aluminum matrix, and interaction also exists between SiC particles, which causing the shape of

serrated-chip to be unique. As shown in Fig. 4c and Fig. 4d, the shape of sawtooth is irregular because of the influence of SiC particles. Some of the sawtooth's tips are not sharp and even flat (marked in red dotted line) and some of the sawtooth's outlines are incomplete and even broken (marked in yellow dotted line).

4.1.2.2. Slip distance

The actual slip distance, which represents the size of the sawtooth, is determined via the method depicted in Fig. 3. As shown in Fig. 4e, feed rates of 0.07 mm/r and 0.12 mm/r yield, ΔX of 67.5 μm –103.4 μm and 127.3 μm –153.3 μm , respectively. ΔX increases (in general) with the feed rate, indicating that increasing feed rate results in more-sufficiently-formed sawtooth.

4.1.2.3. Chip thickness

As shown in Fig. 4f, a feed rate of (i) 0.07 mm/r yields H_1 : 94.8 μm –128.4 μm and H_2 : 135.3 μm –189.4 μm , (ii) 0.12 mm/r yields H_1 : 159.1 μm –215.9 μm and H_2 : 259.2 μm –294.7 μm . The chip thickness is positively correlated with the feed. A transverse-feed method is employed and, hence, a large feed results in a large depth of cutting, and an increase in the chip thickness. In terms of the cutting-speed dependence, the chip thickness varies more significantly at low cutting speeds than at higher speeds. Furthermore, a sawtooth-size limit is observed, i.e., the thickness remains almost constant after reaching a certain value, owing possibly to the obstruction of SiC. When the cutting speed increases, the cutting temperature increases and the thermal softening effect is strengthened, resulting in improved sawtooth production. However, when the sawtooth-size threshold is reached, the chip-thickness limit is also reached and the thickness remains almost constant thereafter.

4.2. Compressive deformation

After obtaining the basic parameters, the compressive deformation characteristics (see Fig. 5) can be obtained with assistance of the theoretical model.

(a)

(b)

Fig. 5. Values of the (a) compressive value, (b) compressive stress, (c) compressive strain, and (d) compressive strain rate

4.2.1. Compression value

Fig. 5a shows the compression value, which reflects the degree of compressive deformation. Values of 17.3 μm –50.0 μm are obtained for cutting speeds and feed rates of 10–350 m/min and 0.07–0.12 mm/r, respectively. The compressive value in practice is greater than 0, showing compressive deformation. There has already been known to be shear deformation in the primary zone. Therefore, the fact that the primary zone undergoes simultaneous compressive deformation and shear deformation reflects internal friction in this zone.

The values increase with increasing feed rate. Similarly, the magnitude of the force increases with increasing feed rate (as shown in Fig. 4a), leading to intensified extrusion of the SiC particles against the Al matrix and interactions between these particles. This intensification enhances the pressing effect exerted by the formed chips on the on-forming chips, contributing to an increase in the degree of compressive deformation. However, the values remain nearly constant with increasing cutting speed. According to Eq. (3), the compressive value can be expressed in terms of actual slip distance, chip root thickness and top thickness. These three parameters remain almost constant when the cutting speed increases (see Fig. 4e and 4f) and, as a result, the compressive value is also (almost) constant.

4.2.2. Compressive stress

The compressive stress ranges from 185.4 MPa to 226.9 MPa, and decreases with increasing feed rate, but increases with increasing cutting speed (see Fig. 5b). According to Eq. (4), this stress is closely correlated with the cutting force (i.e., the main cutting force and the thrust force (Fig. 4a)) and, consequently, increases with increasing cutting speed. Owing to the transverse-feed method, a larger feed rate results in greater depth of cutting (than a smaller feed rate). This leads to a dilution or reduction in the force exerted by the SiC particles on the shear plane,

thereby resulting in a reduction in the compressive stress.

4.2.3. Compressive strain

Compressive strain values of 0.18–0.26 occur at cutting speeds and feed rates of 10–350 m/min and 0.07–0.12 mm/r, respectively (see Fig. 5c). According to Eqs. (3) and (5), both the compressive value and the compressive strain are calculated from the chip thickness, and are described by similar expressions. Therefore, the change law explanations and curve trends of the compressive strain are similar to those of compressive value.

4.2.4. Compressive strain rate

The compressive strain rate ($0.013 \times 10^4/s$ – $0.554 \times 10^4/s$) increases significantly with increasing cutting speed and decreases with increasing feed rate (see Fig. 5d). According to Eq. (6), the compressive strain rate is calculated from the actual slip distance, chip thickness, and cutting speed. Both the actual slip distance and chip thickness change only slightly with the speed (see Fig. 4e and 4f) and, therefore the compressive strain rate exhibits a nearly positive linear dependence on the speed. As the feed rate increases, the hardening effect overcomes the thermal softening effect, leading to a reduction in the strain rate. In addition, due to the transverse feed, the amount of workpiece that must be simultaneously removed by the tool increases when the feed rate increases. This leads to reductions in the removal speed and, accordingly, the strain rate.

4.3. Shear stress and internal friction coefficient

Fig. 6. (a) Shear stress and (b) internal friction coefficient.

4.3.1. Shear stress

Figure 6a shows that, for a given feed rate, the shear stress increases from 39.2 MPa to 107.0 MPa with increasing cutting speed and, for a given cutting speed, decreases with decreasing feed rate. Similarly, the measured force would decrease, because the proportion of the force that SiC particles exert on the tool decreases with

increasing feed rate, thereby leading to a reduction in the calculated shear stress. However, when the cutting speed rises, the hardening effect overcomes the softening effect and, consequently, the shear stress increases.

4.3.2. Internal friction coefficient

The internal friction coefficient of the primary zone increases from 0.21 to 0.47 (Fig. 6b). In fact, for a given feed rate, μ_{in} increases with increasing cutting speed and, for a given cutting speed, decreases with increasing feed rate. The temperature of the primary shear zone increases with rising cutting speed. The material internal flow, extrusion of SiC particles against the Al matrix, and interaction inside the SiC particles become quite complex, owing to this increase. As a result, the friction effect is strengthened, leading to an increase in the internal friction coefficient. Furthermore, the depth of cutting increases with increasing feed rate, leading to an increase in the amount of workpiece that must be simultaneously removed. The corresponding intensity of shear slip and relative movement in the primary deformation zone decreases, contributing to a small internal coefficient.

5. Conclusions

The present work proposes that there is internal friction and compressive deformation in the primary zone. A mathematical model is established which gives methods for calculating internal friction coefficient and compressive characteristics of serrated chip. High-speed orthogonal cutting experiments on SiCp/Al composites are performed at cutting speeds of 10–350 m/min and feed rates of 0.07–0.12 mm/r.

According to the experimental results, affected by SiC particles, the shape of sawtooth is irregular and the stress will be altered by the change in the force exerted by the SiC particles. The internal friction coefficient of the primary zone ranges from 0.21 to 0.47, increases with the cutting speed, and decreases with the feed rate. When the cutting speed increases, the compressive stress (185.4 MPa–226.9 MPa) and compressive strain rate (0.013×10^4 /s– 0.554×10^4 /s) increase, whereas the compression value (17.3 μ m–50.0 μ m) and compressive strain (0.18–0.26) decrease.

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Ethical Approval:

This research does not involve human participants or animals, thus no ethical approval and patient consent are required.

Consent to Participate:

Not applicable.

Consent to Publish:

Not applicable.

Authors Contributions:

Xiaoxuan Lin: Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing.

Wenyuan Yang: Methodology, Investigation, Writing - Original Draft.

Daochun Xu: Conceptualization Ideas, Supervision, Funding acquisition.

Wenbin Li: Supervision.

Simin Ma: Writing - Review & Editing.

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Competing Interests:

The authors declare that they have no competing interests.

Availability of data and materials:

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

Figure 1

Mathematical model for serrated-chip

Figure 2

Experimental setup details.

Figure 3

Schematic showing chip measurement.

(a)

(b)

(c)

(d)

(e)

(f)

Figure 4

Basic parameters: (a) force, (b) SEM image of chip subjected to 0.07 mm/r and 30 m/min after the experiment, (c)–(d) SEM image of chip subjected to 0.12 mm/r and 30 m/min, (e) actual slip distance and (f) chip thickness.

(a)

(b)

(c)

(d)

Figure 5

Values of the (a) compressive value, (b) compressive stress, (c) compressive strain, and (d) compressive strain rate

(a)

(b)

Figure 6

(a) Shear stress and (b) internal friction coefficient.