CIRP Annals - Manufacturing Technology 73 (2024) 49–52

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: https://www.editorialmanager.com/CIRP/default.aspx

An analytical power-based approach to predict orthogonal cutting force for sintered Al2124/SiC metal matrix composite

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Submitted by D. Williams (1), UK

ARTICLE INFO

Article history:
Available online 22 May 2024

Keywords:
Cutting
Modelling
Metal matrix composite

ABSTRACT

This paper presents a new analytical model for prediction of cutting forces in binary materials such as metal matrix composites (MMC) based on the cutting power. The model considers the effect of matrix shearing, reinforcement particles fracture and debonding as well as frictional contact between the tool and the particles to predict cutting forces required to form free surfaces. Linear orthogonal cutting on Al2124-SiC MMC with different cutting speed and depth of cuts were performed. The developed model shows a better performance compared with other available models in the literature to predict cutting forces while the experimental results reveal shearing and fracture as the main chip formation mechanism.

1. Introduction

The presence of finely dispersed secondary particles in Metal matrix composites (MMCs) improves their mechanical properties including strength to weight ratio but presents a significant challenge in machining of these materials. In this context, Al-based MMC materials are increasingly used in demanding applications for automotive, e.g. engine blocks and rotors, aerospace and satellite sectors in e.g. structural elements [1] due to their superior strength to weight ratio, wear resistance and energy absorption. The brittle and abrasive nature of particles, mostly silicon carbide (SiC), alter both plastic deformation as well as chip formation mechanisms during machining. Accelerated tool wear [2], increased cutting forces [3] and deteriorated surface quality [4-6] are commonly reported with increasing the reinforcement particles. It is found that particle debonding [4,7], ductile shear fracture of the matrix [7], as well as particles fracture [8] are the main factors affecting the chip formation and new surface generation mechanisms in machining of these binary alloys Additionally, the size, distribution and relative location of the reinforcement particles are found to affect the chip formation mechanisms and associated cutting force[9,10]. The reinforcement particles reduce the plasticity threshold of the MMCs compared to the base matrix material [9], due to the stress/strain discontinuity at the interfaces, having an compounding effect on the deformation behaviour of the material. Analytical methods based on the required energy of cutting and/or free surface generation, instead of continuum plasticity models, have been repeatedly used to predict machining force in MMCs [5,8-13].

Plastic deformation and fracture energy within the deformation zones [14] as well as mechanical work required to generate chips and new surfaces during machining [15] were the basis of most of these models. However, the former assumed fracture to occur along the newly generated surface, while in the latter fracture was assumed to occur along the shear plane. The literature mainly reports on analytical models developed based on 7000/6000 series aluminium alloys assuming a shear energy partitioning within the deformation zones and pre-existing damage in the material [10] that was found to be not accurate for different material systems or cutting conditions [13]. On the other hand, despite incorporating the energy required for ploughing [11], strain-rate and temperature dependent material properties [11,12] and the volume fraction of particles [8] accuracy of predicted machining forces is shown to be strongly dependents on the material systems and the mechanics of chip formation [11,13]. Most of the literature cover MMCs with particles, Al_2O_3 or SiC, with particle sizes in the order of tens of microns and little is known about the machining of MMCs with submicron sizes which complicates the deformation and failure as well as chip formation mechanisms in the material. These could generate submicron surface integrity defects affecting the performance of the parts as well as complex wear mechanisms. Therefore, a better physics-based prediction of machining forces will improve process design for enhanced tool performance of tool life of the produced parts.

An analytical model is presented for prediction of cutting forces in orthogonal cutting of a AA2124-SiC metal matrix composite material produced by the powder metallurgy and sintering process. Components of energy required for the generation of a new surface, plastic deformation of the matrix, and multiple failure mechanisms of particles together were considered in the model. The predicted forces are compared with the results of available models in the [13,14] tuned for the tested material as well as experimentally measured forces in a linear orthogonal setup at various cutting conditions.

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https://doi.org/10.1016/j.cirp.2024.04.045

2. Orthogonal cutting tests

2.1. Experimental setup

Linear orthogonal cutting tests were conducted on a AA2124-based MMC with 0.3 µm SiC particles with 17 % volume fraction (AMC217XG-Al/SiC). The material was produced by a powder metallurgy technique and detail analysis of microstructural properties are reported in [16]. Square section samples (25 mm) with a thickness of 2.5 mm were cut from a bar stock using WEDM and a milling machine (XYZ- 1060 HS) was used to perform dry linear cuts. Uncoated carbide inserts (TCMW110204H13A) were used for the cutting experiments, while the cutting forces were measured with a Kistler dynamometer, Fig. 1a.

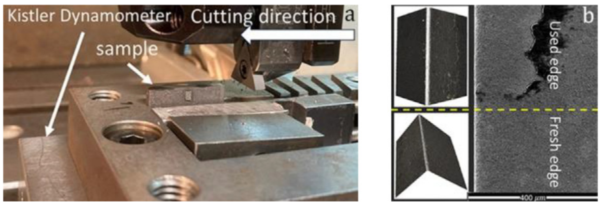

Fig. 1. (a) Experimental setup with the sample fixed on the dynamometer, and (b) 3D topography and SEM micrographs of the cutting edge before and after the cuts.

The geometry of cutting edges were measured using the Alicona-G3 infinite focus microscope before and after the machining trials, Fig. 1b, to ensure the consistency of the rake angle (γ), zero degree, the edge radius (r), 10 µm, for all tests. A fresh cutting edge was used for each experiment, total cutting distance of 25 mm. Different combinations of Cutting speeds, V_C, (2, 6, 20 and 30 m/min) and depths of cut, a_0, (0.05, 0.1 and 0.2 mm) were used to obtain the required parameters for development and validation of the model. The cutting tests were interrupted at the lower cutting speeds, through the rapid disengagement of the tool, to preserve and identify deformation and failure mechanisms of the material to include the required energy terms in the model. The resulting chip sections were metallographically prepared to determine the actual uncut and cut chip thicknesses.

2.2. Cutting tests results

Fig. 2a shows a representative machining forces evolution with tool displacement showing zero out of plane forces. Each cutting trial was repeated three times and the average values together with the associated standard errors for all the applied cutting conditions are reported in Fig. 2b. The maximum depth of cut was less than 10 % of the sample thickness confirming the plane strain condition during the chip formation.

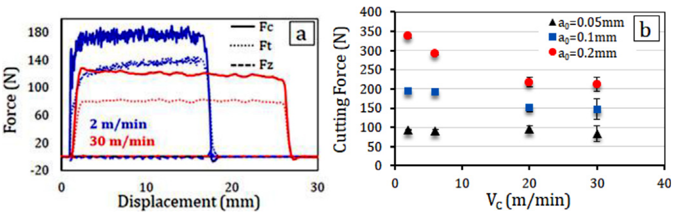

Fig. 2. (a)Machining forces evolution for representative cutting conditions and (b) average cutting forces together with the standard error for all the experiments.

The measured average cutting forces in Fig 2b and chip section analysis, Fig. 3, demonstrate that at lower depth of cut the chip formation becomes independent of cutting speed. This, together with the analysis of the measured forces proposed by Atkins [14] highlights the significance of energy required for free surface formation for this material. The analysis of the machined surface, Fig. 4, reveals several active mechanisms at the tertiary deformation zone including

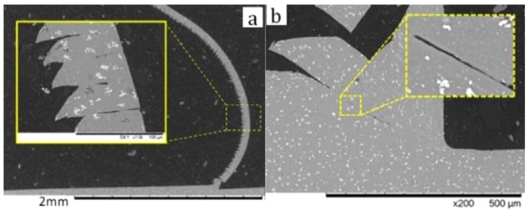

Fig. 3. serrated chips showing localised deformation and shear fracture as the main mechanisms within the primary deformation zone and ahead of the cutting tool (a) at $V_C = 30m/min$and (b) $V_C = 2m/min$.

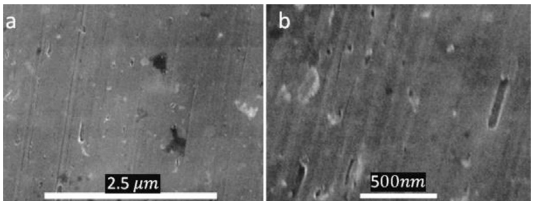

Fig. 4. micrographs of generated surface at $V_C = 30m/min$ showing different SiC particle interaction mechanisms including (a, b) pull out, push down and (b) fracture of particles resulting in ploughing motion.

push down, fracture of particle resulting in ploughing action as well as pull out from the matrix.

Standard tensile and shear tests were conducted using sample geometries reported in [17] and demonstrated a relatively brittle nature of the studied material.

Hence, conventional approach to determine the shear strength based on the plastic flow stress as used in [12] is not applicable. Additionally, the investigated MMC has a low temperature and strain rate sensitivity [16] therefore, the use of strain rate and temperature dependent material models proposed in [8,11] are not relevant for this particular grade of MMC due to the inherent mechanical properties of the matrix phase.

3. Analytical model for cutting force prediction

The key power consuming phenomena were considered in developing the analytical model as suggested in [14]. It was assumed that the total cutting power is required for plastic deformation in the shear zone (P_{shear}), frictional work in the secondary and tertiary deformation zones ($P_{friction}$) and the specific energy required to form free surfaces around the cutting edge (P_{fs}):

$$F_c V_c = P_{shear} + P_{friction} + P_{fs} \quad (1)$$

An upper-bound and lower-bound functions were developed to consider the number of particles in the shear plane that affects the shear strain energy of the matrix. The lower bound value considered particles that lie perfectly on a straight shear line, while in the upper-bound model particles were assumed to fill a rectangular section with a specified volume fraction (Fig. 5). therefore, the shear strength at the shear plane is defined as:

$$\tau_s = \tau_{y,\ matrix}\left(1 - v_f\right) + \tau_{f,\ particle} v_f \quad (2)$$

The power required for the frictional work at the rake and flank face of the tool were determined based on the average coefficient of friction obtained from the experimental data as [15]:

$$P_{friction} = [F_C \sec(\beta - \gamma)\sin\beta]\frac{V_C \sin\phi}{\cos(\phi - \gamma)} \quad (3)$$

where $\gamma,\ \beta,\ \phi$ are rake, friction, and shear plane angles, respectively. In addition to the shear fracture of matrix [14], the particles are either fractured, pushed down, or pulled-out of the matrix [10,18] as the cutting tool moves forward. The power required to push-down a particle from the stagnation point ahead of the tool can be determined, based on the new surface generation hypothesis [14], by:

$$P^*_{pushdown} = \frac{\pi}{2} R_m + \frac{\sigma_{y,matrix} \pi d_p (2r_{tn} + d_p)}{4r_{tn} + 2d_p} \tag{4}$$

where R_m and $\sigma_{y,matix}$ are the specific free surface energy (fracture toughness) and yield strength of the matrix, respectively, and d_p, and r_{tn} represent the particle diameter and cutting edge radius. The relevant mechanical proerties are reported in Table 1.

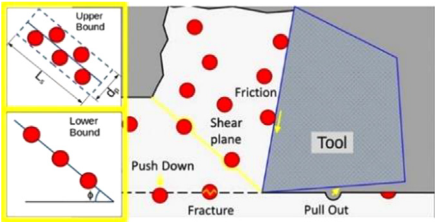

Fig. 5. active mechanisms in chip formation of MMC material showing the upper and lower bound assumptions for the effect of particles (red dots) in the shear plane.

Table 1
Mechanical properties of AMC217XG-Al-SiC.

Property	Value
Compressive strength σ_y(MPa) [16]	543
Shear yield stress (MPa) based on [14]	135
Specific free surface of energy of matrix R_m(KJ m^{-2}) [14]	6
Specific free surface of energy of reinforcement R_p(KJ m^{-2})	52.55
Specific particle fracture energy (KJ m^{-1}) (It is used for the Paramanik model) [13]	0.01

Therefore, the work required to form a new surface in the sample with a width of w, and a particle volume fraction of v_f can be calculated as the combined effect of the matrix deformation and fracture, particles ploughing effects as well as the energy required to fracture particles align the cutting plane:

$$P_{fs} = v_f \left[\Gamma R_p w V_C + (1 - \Gamma) P^*_{pushdown} w V_C \right] + (1 - v_f) R_m w V_C \tag{5}$$

where R_p is the specific free surface energy and Γ is the percentage of the broken reinforcement particles. The cutting force can then be predicted using the Eq. (6) based on the model proposed in [14]:

$$F_C V_C = \tau_s \gamma_s a_0 w V_C + [F_C \sec(\beta - \alpha_r) \sin\beta] \frac{V_C \sin\phi}{\cos(\phi - \alpha)} + P_{fs} \tag{6}$$

As the fracture properties of the studied material are not identical with a monolithic matrix material, a numerical approach based on the Newton-Raphson method was adopted to determine some material constants such as Z and R (specific free surface energy) [14]. These were required to calculate cutting forces using Atkins [14] and Pramanik [13] models to compare the accuracy of the proposed model in this study. The work of [15] and associated modelling approaches were not considered as the chip formation mechanisms were not consistent with the observed experimental results or material properties.

4. Results and discussions

Fig. 6 shows the comparison of the predicted cutting forces according to the developed model (Mod), Atkins (At) and Pramanik (Pr) models are compared with the experimental measurements at cutting speeds of 2, 6, 20 and 30 m/min and various depth of cuts. The model runs under 1 min for all the applied parameters using a 4 cores workstation with 16GB of RAM.

All the models underpredict the required cutting force at any cutting condition and demonstrate a declining cutting force with the increased cutting velocities, as expected. This is more prominent as the depth of cut increases (Fig. 6c) since the plastic deformation becomes the main chip formation mechanism. However, the effect of matrix material ploughing and reinforcement particles effects as well

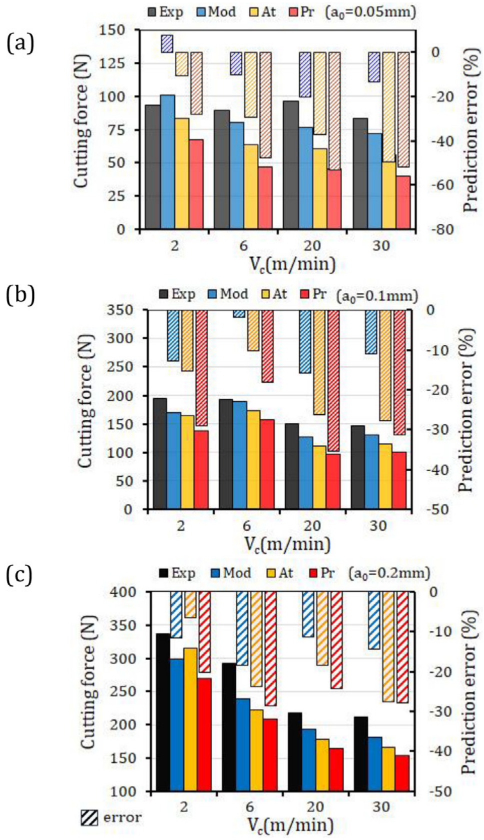

Fig. 6. comparison of the predicted cutting force predictions vs. experimentally measured average forces for the depth of cut of (a) 0.05 mm, (b) 0.1 mm and (c) 0.2 mm at various cutting speeds. Solid bars show the predicted values using the proposed model (Mod, blue), Atkins (At, amber) and Pramanik (Pr, red) models. The error of predictions is demonstrated by the hatched bars and the secondary vertical axis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

as free surface formation become more significant as the depth of cut reduces. Since the energy required to overcome these phenomena is constant, regardless of the cutting speed variations, cutting forces required to remove the chip at lower depth of cut become almost independent of the applied cutting speed.

The proposed model (solid blue bars) outperforms others with errors of less than 20 % across the applied cutting conditions. However, as the cutting speed increases, the models performance drop with the largest error associated with the "Pr" model. The errors in the predicted forces by the Atkins and Pramanik models (hatched amber and red bars) increase at lower depth of cuts while the proposed model shows an inverse behaviour with a better performance at lower depth of cut. This implies that the additional terms associated with the particles fracture and ploughing have enhanced the cutting forces prediction when the ploughing is a dominant mechanism.

However, increasing the depth of cut activates additional shear mechanisms, most importantly in the secondary deformation zone ahead of the rake face of the tool as shown in Fig. 7. This additional mechanism becomes dominant by increasing the uncut chip

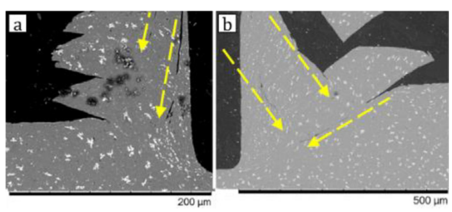

Fig. 7. Shear fracture within the deformation zones in the direction of maximum shear stress for samples with the depth of cut of (a) 0.1 mm and (b) 0.2 mm. The arrows indicate the observed fracture loci.

thickness and could be the possible source of error in the developed mode. The presence of SiC particles could be the main driver for this mechanisms and such a phenomenon was not observed in orthogonal machining of a AA2024 monolithic material with identical cutting conditions [19].

Therefore, it is crucially important to experimentally, or numerically, determine the shear strength of the material rather can using a continuum plasticity approach as reported in [8]. The contribution of particle fracture and debonding to the overall energy consumption is one of the main assumptions for analytical models of composite materials and particularly MMCs [11,12]. Although it was assumed that 50 % of the particles are fractured the results of Fig. 6, experimental data is required to determine this and consider its effect according to the rule of mixtures as defined for the proposed mode.

Fig. 8 shows the associated error in the calculated cutting forces using various assumptions for particles fracture (F) or push down (P). Based on the calculated cutting force prediction error, the push-down mechanism is dominant effect at the lower depth of cut and its effect diminishes as the cutting speed increases. However, as the depth of cut increases, the contribution of particles fracture becomes consistent by the cutting velocity. Therefore, the percentage of broken particles (Γ) in Eq. (5) should be dependent on the applied uncut chip thickness. Although, Γ = 50% provides a better prediction result compared with the other available physics-based models. Additionally, a bespoke friction model is required to better determine the frictional condition in the tertiary deformation zone covering the distribution of the particles in the frictional contact zone.

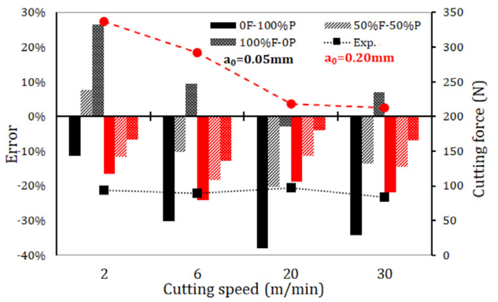

Fig. 8. The effect of fracture (F) and push-down (P) mechanisms on the cutting force prediction errors compared with the measured data (Exp.) at different V_c and a_0=0.05 and 0.1, black and red features, respectively.

5. Conclusions

A new analytical model for prediction of the cutting for in machining of a AA2124-Sic metal matrix composite was proposed, implemented, and tested for different uncut chip thickness and cutting speeds of up to 30 m/min. The required energy during chip formation to overcome not only the shear deformation along the shear plane, but also a free surface generation and reinforcement particles fracture were considered in the model. The proposed methodology outperformed the previously developed models compared with the measured cutting forces. The effects of particles on the required cutting energy are directly dependent on the geometry of cut, including uncut chip thickness, and the cutting speed and this is a constant factor when larger chips are formed at higher cutting forces. Additional understanding of shear failure within the primary and secondary zones as well as frictional mechanisms in the tertiary deformation zone together with an appropriate flow stress model are required to incorporate the effect of shear fracture and friction energy for chip formation. The future studies should focus to develop the required friction model as a function of particles size and their distribution as well as a representative material and damage model for a higher prediction accuracy.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Hassan Ghadbeigi: Conceptualization, Methodology, Funding acquisition, Supervision, Investigation, Resources, Visualization, Writing – original draft, Writing – review & editing. **Saeid Taghizadeh:** Investigation, Software, Formal analysis, Writing – original draft. **Sabino Ayvar-Soberanis:** Resources, Writing – review & editing. **Will Baines:** Investigation, Software, Formal analysis, Visualization.

Acknowledgements

This research was funded as part of the SENSYCUT project by EPSRC (EP/v055011/1). The technical support provided by Sandvik Coromant- UK is also acknowledged.

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