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On machining modeling of metal matrix composites: A novel comprehensive constitutive equation

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ABSTRACT

Exceptional mechanical characteristics make metal matrix composites (MMCs) a popular choice in various industries. However, the knowledge related to the behavior of MMCs during machining is very limited. This is mainly due to complications in mechanics of chip formation arising from existence of very hard reinforcements. This paper aims to improve the understanding of MMC's behavior during cutting by developing a novel constitutive equation, which describes the explicit relationship between MMC's behavior during cutting and its main unique features, namely reinforcement size and volume fraction. Comparison with machining experiments for various MMCs verifies the validity of the proposed model.

1. Introduction

Composite materials are defined as combinations of two or more materials with diverse chemical and mechanical properties. The matrix phase transfers load and supports the integrity of the structure while the particle phase provides enhancement to the mechanical properties of the composite. Among composites, metal matrix composites have become the widely used materials in many industrial applications because of their outstanding strength-to-weight ratio and wear resistance. Some examples of MMC applications are in cylinder liners for internal combustion engines, ventral fins and lower drag brace landing gears in fighter planes, and helicopter blades [1]. Although composite materials are commonly manufactured to near net shape, machining processes are usually employed to achieve the desired dimensional accuracy of the final product.

Machining of metal matrix composites is a challenging task in comparison to the traditionally used metals in industry. This is mainly due to the existence of hard ceramic reinforcements in MMCs which have similar hardness characteristics as the cutting tools. During machining, these hard ceramic particles are rubbed against the cutting tool and severely damage the tool surface and consequently cause excessive tool wear. Excessive tool wear, in turn, causes various types of damage in the machined surface. Moreover, the complications related to the mechanics of chip formation during MMC cutting further increase the complexity of the cutting process. These obstacles arise from the interactions between cutting tool, matrix, and reinforcements. Thus, machining MMCs is considered to be a challenging task. Hence, a comprehensive understanding of the behavior of MMCs during machining is considered an asset in achieving the optimal process parameters.

Successful modeling of machining process requires better understanding of the material behavior under the typical temperature and strain rate encountered during metal cutting. The material behavior under various conditions can be described using a proper constitutive equation which includes the main parameters that affect the material behavior including strain, strain rate, and temperature. In addition to these parameters, particle size and volume fraction are particularly important for modeling MMC materials during machining, where alterations of these parameters greatly affect the MMC behavior during cutting.

Several machinability studies of MMCs were reported [1–4], however, very few analytical models for analysis of the process exist. Among these models are the force models [5–7] and the wear models [8,9]. These models, particularly the ones used for depicting the mechanics of cutting MMCs, have been relatively successful in defining the effects of some unique features of MMCs, such as volume fraction and size of reinforcements, on different process outputs. However, they all rely on constitutive equations that are usually utilized for modeling monolithic materials. As a result, in these constitutive equations, the relationship between the process parameters and the unique MMC features is not

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Nomenclature

A Johnson–Cook plasticity constant [MPa]
A_c uncut chip cross-sectional area [m^2]
A_i contact area at the particle–tool interface [m^2]
b width of cut [m]
b_{1T} true chip width [m]
B Johnson–Cook plasticity constant [MPa]
Br Briks similarity criterion
C Johnson–Cook plasticity constant
d particle diameter [m]
d_N Weibull probability normalizing constant [m]
F_C cutting force [N]
F_f MMC cutting friction force [N]
$F_{f-2body}$ two-body abrasion friction [N]
$F_{f-3body}$ three-body rolling friction [N]
F_{fM} friction at the tool–matrix interface [N]
F_{fP} friction at the tool–particle interface [N]
H_1, H_2, H_3 constitutive equation empirical constants
H_{tool} tool material Vickers hardness
l_c tool–chip contact length [m]
m Johnson–Cook plasticity constant
n Johnson–Cook plasticity constant
N_p number of particles at the tool–chip interface
P_c total cutting power consumption [W]
P_{deb} power required for debonding of particles [W]
P_{fns} power required for formation of new surfaces [W]
P_{fr} probability of fracture of reinforcement
P_{mnc} power consumption due to effect of minor cutting edge [W]
P_{pd} power for plastic deformation [W]
P_{tc} power spent at tool–chip interface [W]
P_{tw} power spent at tool–workpiece interface [W]
q Weibull inhomogeneity factor
R MMC particle radius [m]
t_{1T} true uncut chip thickness [m]
t_{2body} fraction of particles involved in two-body abrasion
t_n normal traction [Pa]
t_n^o maximum normal traction [Pa]
t_s first direction shear traction [Pa]
t_s^o maximum first direction shear traction [Pa]
t_t second direction shear traction [Pa]
t_t^o maximum second direction shear traction [Pa]
T material temperature [°C]
T_{melt} material melting temperature [°C]
$T_{transition}$ transition temperature [°C]
v cutting speed [m/s]
V_f MMC volume fraction

Greek letters

α flank angle [deg]
γ rake angle [deg]
δ_n separation at matrix–particle interface [m]
δ_n^c characteristic length of matrix–particle interface [m]
δ_{p0} tool–particle groove depth [m]
ϵ equivalent plastic strain
ϵ^f equivalent strain to fracture
$\dot{\epsilon}$ plastic strain rate [1/s]
$\dot{\epsilon}_0$ reference strain rate [1/s]
ζ chip compression ratio
θ_p tool–particle angle of contact [deg]
κ_{r1} minor cutting edge angle [deg]
λ matrix–particle interface equation non-dimensional parameter
μ_{3body} three-body friction coefficient
ν Poisson's ratio
ρ_{ce} cutting edge radius [m]
σ flow stress [Pa]
σ_0 Weibull probability normalizing constant [Pa]
$\sigma_{cracked}$ stress in cracked part of primary shear zone [Pa]
$\sigma_{debonded}$ stress in debonded part of primary shear zone [Pa]
$\sigma_{max,int}$ matrix–particle interface strength [Pa]
σ_P particle stress [Pa]
σ_R ultimate tensile strength of matrix material [Pa]
$\sigma_{undamaged}$ stress in undamaged part of primary shear zone [Pa]
τ_c average shear stress at the tool–chip contact [Pa]
τ_y shear strength of the matrix material [Pa]
ϕ work of separation at matrix–particle interface [J]

explicitly included. Instead, the effect of particle size and volume fraction is implicitly embedded in an equivalent constitutive equation [10] after calibration for each volume fraction and particle size.

This paper presents a novel constitutive model suitable for simulation of the behavior of particulate MMCs during machining. This model offers a meaningful relationship between the MMC's behavior and its unique features, namely particle size and volume fraction. Different mechanisms of material behavior in the primary shear zone during chip formation are investigated. For each part, the main three MMC phases, namely the ductile matrix, the brittle particle, and the cohesive particle–matrix interface, are modeled. These models are then incorporated in MMC constitutive equation. The resulting constitutive model is in the form of a relation between flow stress and process and material characteristics, namely strain, strain rate, temperature, particle size, and volume fraction. In order to validate the proposed constitutive equation, it is utilized in an energy-based model for prediction of cutting forces during cutting different MMC materials which include different matrices and different particle sizes and volume fractions. The predicted values are compared to the experimentally measured data.

2. Material constitutive modeling

Mechanics of chip formation and cutting process are affected by the mechanical behavior of workpiece material during machining. Constitutive models are used in process modeling and simulation to portray the unique material behavior. These material constitutive models are usually in the form of mathematical equations which include flow stress, strain, strain rate, and temperature. For metal matrix campsites, the constitutive model should also incorporate the volume fraction and size of reinforcements.

Chip is formed when the workpiece material is plastically deformed and sheared along the shear zone by means of the cutting tool. A major part of plastic deformation during metal removal occurs in the primary shear zone. Thus, a constitutive equation for the cutting process should provide an estimation of stress in this zone. As shown in Fig. 1, an element in MMC shear zone can consist of three parts, namely undamaged material, debonded particles where the particle–matrix bond is degraded, and cracked particles. According to the rule of mixtures, the flow stress in this zone is assumed to be a linear combination of flow