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Evaluation of cutting force during machining of aluminium metal matrix composite by finite element modelling and simulation using ABAQUS 6.13

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Abstract*— Aluminium metal matrix composites are used widely in aerospace and automobile applications due to their superior mechanical properties. Machining of aluminium metal matrix composites is difficult due to the presence of hard abrasive particles. The Al6061 and, Al6063 metal matrix composites reinforced by silicon carbide, alumina, boron carbide are developed and machined by researchers. Cutting forces play an important role in assessing machinability of the aluminium metal matrix composites. This paper is an attempt of development of a finite element model and machining simulation to determine cutting force. ABAQUS 6.13 software is used to perform machining simulation on aluminium metal matrix composites with tungsten carbide inserts.

Keywords*— Aluminium metal matrix composite, cutting force, finite element model, machining simulation, ABAQUS.

I. INTRODUCTION

The metal matrix composites (MMCs) are widely used in aerospace, automobile, electronic packaging and, sports industries due to their improved mechanical properties such as excellent strength to weight ratio, wear resistance etc. [1] [2] Though composites are produced to the near net shape but sometimes machining of these parts is also needed. For machining of metal matrix composites, poly crystalline diamond (PCD) or Chemical vapor deposition diamond (CVD) tools have been proposed by researchers. In some cases, tungsten carbide tools are also used for machining of aluminium metal matrix composite (AMMC). To understand the mechanics of machining processes, various studies have been conducted in the past. Both analytical and finite element methods are applied by researchers. Pramanik et al. [3] proposed a mechanics model to predict cutting forces in machining of AMMC. The model considers that resultant cutting force consists of components of forces due to chip formation, ploughing and, particle fracture and displacement. The study indicates that force due to chip formation is much higher than those due to ploughing and particle fracture. Y. Karpat [4] developed a material model for titanium alloy considering strain, strain rate and temperature. Davim et al. [5] presented a model for machining of MMCs with PCD inserts. The model is useful in the determination of values for machining parameters like compression ratio, friction angle and, shear angle. The paper discusses a way to model and simulate turning of aluminium metal matrix composite and assess cutting force generated.

II. LITERATURE REVIEW

Researchers have conducted experimental studies on aluminium metal matrix composites and recorded cutting forces generated during machining. Srinivasan et al. [6] performed single pass dry turning of LM25 metal matrix composite using uncoated tungsten carbide tool inserts. Machining parameters were varied during the experiments e.g. cutting speed was varied between 100-125 mpm, feed between 0.1-0.2 mm/rev and, depth of cut between 0.5-1.0 mm. Shetty et al. [7] conducted turning on Al6061-SiC metal matrix composite using CBN (KB-90) tool inserts. Machining parameters were varied during the experiments e.g. cutting speed was varied between 45-101 mpm, feed between 0.11-0.25 mm/rev and, depth of cut between 0.5-1.0 mm. Davim et al. [8] conducted turning on Al356-SiC metal matrix composite using TMCW 16T308F tool inserts. Machining parameters were varied during the experiments e.g. cutting speed was varied between 250-700 mpm, feed between 0.05-0.20 mm/rev and, depth of cut was kept constant as 1.0 mm.
Arrazola [9] proposed a finite element modelling of chip formation process setup with Arbitrary Lagrangian Eulerian (ALE) formulation using ABAQUS 6.3 software. The experimental validation of the model showed a good agreement. The workpiece material is modeled using the Johnson-Cook constitutive law. The Coulomb's friction law governs tool-chip interface contact. Fathipour [10] performed conducted numerical analysis of machining of aluminium using ABAQUS software. The workpiece material is modeled using the Johnson-Cook law. Surface to surface contact and Coulomb friction model was used for contact during machining.

III. FINITE ELEMENT MODELLING OF MACHINING OF AMMC

Finite element analysis (FEA) of metal cutting has been carried out by researchers in the past. These studies give an idea about modeling of machining of composite materials, the constitutive behaviour of composite, mechanism of chip formation and, tool-chip interaction etc. [11]. MMCs contain reinforcement and are different from metals. Various failure mechanisms that occur during the machining of MMCs are: fracture of the reinforcing particles, formation of voids by debonding at the particle/matrix interface, growth and merging of voids in the matrix.

Finite Element Analysis for machining simulations uses three methods namely Eulerian, Lagrangian and Arbitrary Lagrangian Eulerian (ALE) methods [9]. The ALE formulation combines both Eulerian and Lagrangian formulations. In this method, the finite element mesh is neither fixed spatially nor attached to the work material. The mesh is allowed to flow with the work material. In this way, severe distortion of the elements is avoided. This method is widely used in machining simulation.

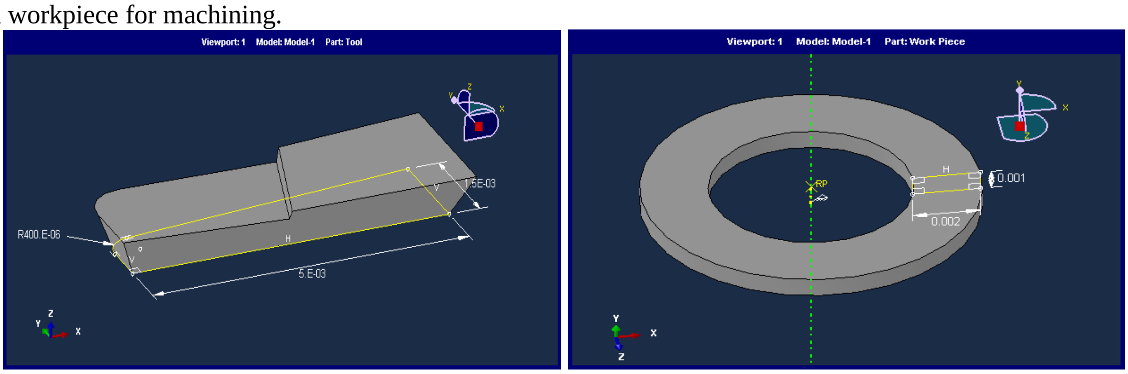
The considerable amount of friction, due to the tool-chip interaction, is involved in machining. The coefficient of friction can be determined experimentally for a particular work and tool material combination. In metal cutting simulations, Coulomb friction model has been used. Coulomb friction law and Tresca shear stress limit are used to model the friction at the chip-tool interface [12].

Analytical modeling of MMCs machining is not able to address all the aforesaid failure mechanisms. Finite element simulations of MMC machining are able to predict mechanisms such as particles flow in the chip root region, debonding of the particles in the secondary zone, tool–workpiece interaction and, pull-out of the particles.

1. Input parameters in finite element modeling of machining of AMMC using ABAQUS

(i) Material model: Mechanical properties, J-C constants of Al6101-SiC, tables I, II and, III are taken from published research literature [13]. Tool insert made of tungsten carbide is used for machining simulation. Properties of tool material, table IV, are taken from published research data [14]. These are input to ABAQUS while developing FEA model.
(ii) Friction: Coefficient of friction is taken as 0.31.
(iii) Damage criteria: Johnson Cook damage criteria.
(iv) FEA Approach: ALE approach.
(v) Element type: Element types for workpiece C3D8RT and for tool insert C3D4T.
(vi) Mesh size: Approx global size for workpiece 0.0001 and for tool 0.0003

Some of the images of ABAQUS models are shown in figure 1. Figure 2 shows boundary conditions with assembly of tool and workpiece for machining.



(a) **(b)**

Fig. 1 Model of (a) cutting tool insert & (b) workpiece

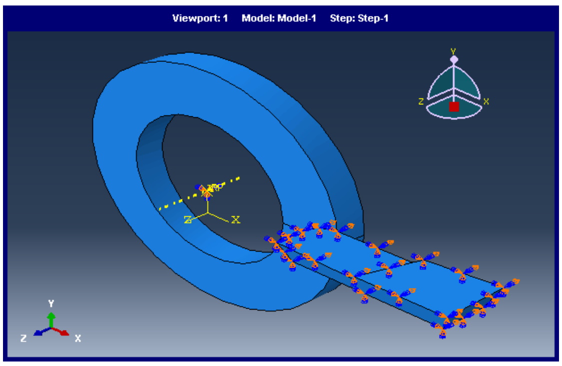


Fig. 2 Boundary conditions

TABLE I
MECHANICAL & THERMAL PROPERTIES OF AL6061-SIC COMPOSITE

Density	Young's Modulus	Poisson's ratio	Thermal conductivity	Specific heat
Kg/m^3	GPa	-	W/mK	J/g°C
2700	68.9	0.33	167	0.896

TABLE II

J-C MATERIAL MODEL PARAMETERS FOR AL6061-SIC COMPOSITE

A	B	C	n	m	T_{room}	T_{melt}
MPa	MPa	-	-	-	°C	°C
324.1	113.8	0.002	0.42	1.34	25	652

TABLE III

J-C DAMAGE MODEL PARAMETERS

D1	D2	D3	D4	D5
-0.77	1.45	0.47	0.0	1.6

TABLE IV

PROPERTIES OF TUNGSTEN CARBIDE

Density	Young's Modulus	Poisson's Ratio	Thermal Conductivity	Specific heat
Kg/m^3	GPa	-	W/m-K	J/kg-°C
11900	534	0.22	50	400

IV. RESULTS AND DISCUSSION

In machining simulations work material (Al6061-SiC composite), tool material (tungsten carbide) and, cutting speed are kept constant while feed, depth of cut are varied. Results of cutting force obtained by finite element machining simulation using ABAQUS 6.13 and experimental cutting forces obtained by researchers in the past are presented in table V. It is observed that ABAQUS simulation cutting force is close to experimental force for same machining parameters.

TABLE V

RESULTANT CUTTING FORCE

Shetty [7] experiment No.	Cutting speed	Feed	Depth of cut	Resultant cutting force	
				Experimental	ABAQUS simulation
	V	f	d	R_E	R_S
	m/min	mm/rev	mm	N	N
17	104	0.11	0.5	243.57	221.94
21	104	0.11	1.0	293.49	274.30
25	104	0.25	0.5	259.32	276.95
29	104	0.25	1.0	235.27	222.04

Figure 3 shows image of material removal and resultant cutting force at an instant during machining simulation using ABAQUS 6.13. The resultant cutting force has three components e.g. radial force component, cutting force component and, feed force component. As cutting tool penetrates into the work and machining commences extra material in the form of chips is removed from the workpiece. Figure indicates that discontinuous types of chips are generated during machining simulation.

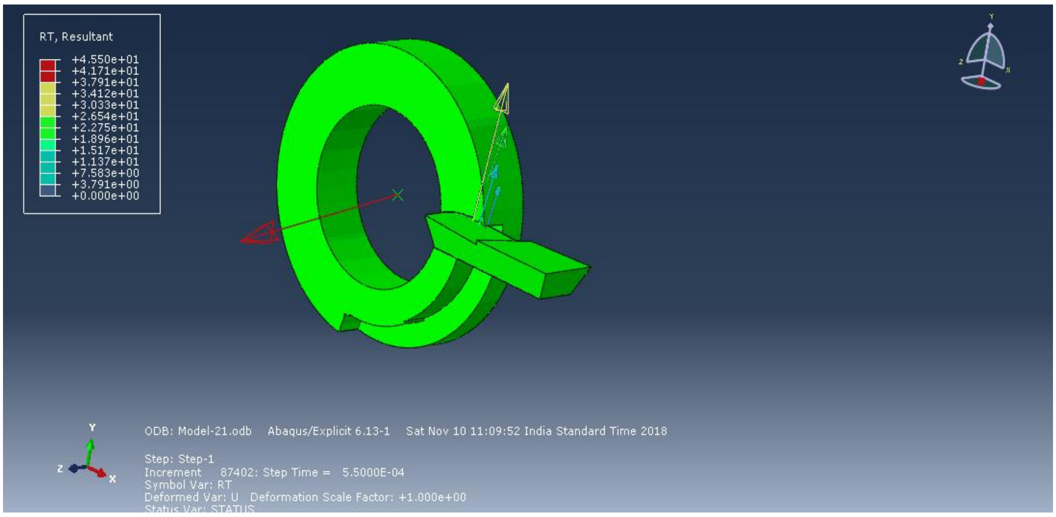


Fig. 3 Material removal and resultant cutting force at an instant during machining

V. CONCLUSIONS

Machining a particulate metal matrix composite is a difficult task due to the presence of reinforcement particles. Machinability of the AMMC depends on machining parameters including cutting speed, feed, depth of cut, tool material, tool geometry etc. Assessment of cutting force requires experimentation which is time consuming, labour oriented and, costly. Machining simulation using finite element analysis tool like ABAQUS is helpful in assessing cutting force and hence machinability of AMMC. From the study it is clear that cutting force results of finite element simulation are close to experimental (experiments conducted by researchers in the past) results. Hence machining simulation can be utilized for assessment of cutting forces.

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