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ANALYSIS OF MECHANICAL CHARACTERISTICS OF FACE MILLING PROCESS OF Ti6Al4V ALLOY USING EXPERIMENTAL AND SIMULATION DATA

This paper presents experimental and 3D FEM simulation results obtained for the Johnson-Cook material constitutive model and variable cutting conditions. Face milling tests were carried out using a Ti6Al4V titanium alloy as the workpiece and coated carbide indexable inserts. CAD models of the cutting tool insert and the face milling head were generated and implemented into FEM package used. The machining conditions were selected based on real production data from aerospace sector. In particular, changes of power and specific cutting energy were analyzed in terms of the rotation angle of the milling head and the ratio of the uncut chip thickness against the cutting edge radius.

Nomenclature

SCE	-	Specific Cutting Energy
FEM	-	Finite Element Methods
HPC	-	High Performance Cutting
HRSA	-	Heat Resistant Superalloys
HSC	-	High Speed Cutting
JC	-	Johnson-Cook material model
UCT, h	-	Uncut Chip Thickness
v_c	-	cutting speed
a_p	-	depth of cut
a_e	-	width of cut
f	-	feed
r_ε	-	tool nose radius
r_n	-	cutting edge radius
A, B, C, n, m	-	Johnson-Cook model parameters
ϕ_0	-	head rotation angle
ε_0^p	-	strain rate
κ_r	-	setting angle

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1. INTRODUCTION

The development of manufacturing processes requires new and robust methods of technological process optimization which are tested in the implementation phase. For instance, in the machining practice engineers modify tool paths by means of the selection of the technological parameters and cutting tool configurations. All of these activities are based on expensive experiments and technological tests performed in production environment.

At present, the FEM based simulation is a basic engineering tool which accelerates and facilitates the successful solution of this problem. However, the basic obstacle in the engineering application of the FEM technique is the lack of an accurate constitutive material model fitted to various workpiece and cutting tool materials [1],[2],[3]. In particular, more accurate and complete constitutive material models which consider the appropriate mechanical thermophysical properties of both the workpiece and tool materials are needed [4],[5],[6]. A distinct controversy appears in the modeling of aerospace construction materials, including the heat resistant superalloys (HRSA), basically a group of titanium and nickel-based alloys [2],[8]. The elaboration of an accurate constitutive model depends on important technical possibilities and limitations [3],[8].

The determination of the appropriate parameters of the constitutive material model requires numerous experimental tests and data analyses. In particular, reverse solutions have also been proposed [9]. Current trends show that the FEM constitutive model should satisfy the High Speed Cutting (HSC) and High Performance Cutting (HPC), which require the implementation of high strain rate tests. Moreover, the material modeling should cover a wide spectrum of cutting tool materials including multilayer coated and composite tools.

In the light of all mentioned problems, the paper is focused on the influence of the Johnson-Cook (JC) constitutive material model on the simulation results of 3D face milling operations of an Ti6Al4V titanium alloy using TiAlN coated H10 carbide insert. The FEM predictions were compared with the experimental data.

2. METHODOLOGY OF INVESTIGATIONS

The tests were carried out for a flat milling with fife-flute cutter-head type H490 F90AX D050-6-22-09 with sintered carbide insert H10 type ANCX090416PDR from Iscar coated with TiAlN layer of 3 μm thick. The 3D CAD model of the insert (a) and the model of the tool edge used in FEM simulation (b) are presented in Fig. 1.

In order to increase the nodal mesh density at the junction between the cutting edge and the workpiece material, the settings of AE were modified. The meshing strategy was based on own matching parameter data presented in [10]. The defined tool insert model with appropriate settings resulting from its location in the cutter head were imported correctly to the FEM simulation system. The experimental and simulation conditions are specified in Table 1. Additionally, it was necessary to determine the initial angle of head rotation ϕ_0= 37°. Fig. 2 visualizes technological parameters introduced in FEM package along with the xyz coordinate system, three components of the resultant cutting force and initial angle of head rotation ϕ_0.

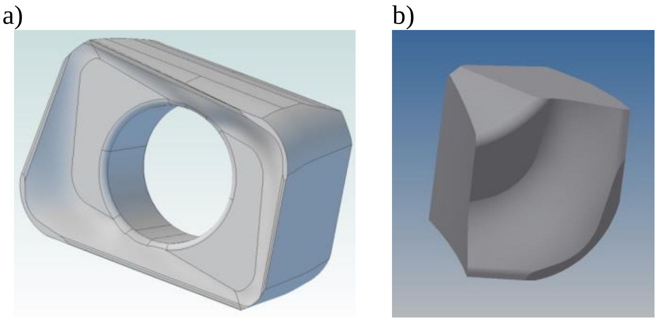

Fig. 1. CAD model of cutting tool inserts (a) with magnified cutting edge (b)

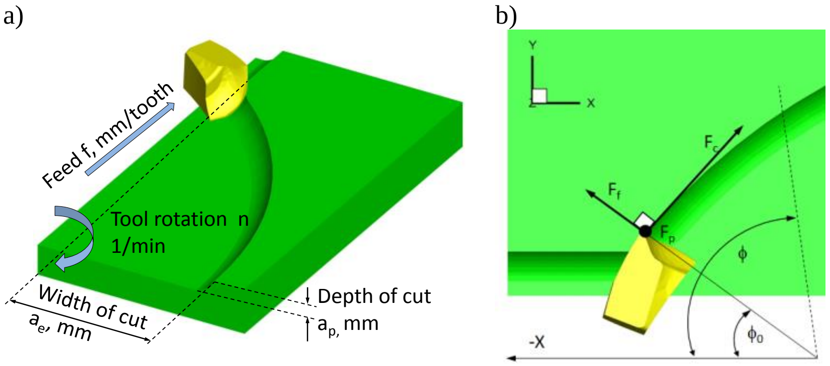

Fig. 2. Technological parameters (a) and coordinate axes with defined vectors of cutting force components in the FEM system (b). Fixed initial angle of head rotation ϕ_0=37°

In this study the experimental results were compared with simulation outputs obtained for Johnson-Cook model (JC) constitutive material model, which is predominantly used for modelling of machining processes of metallic alloys [2]. The parameters for the JC constitutive model used in this study are specified in Table 2.

Table 1. Configurations of experimental and numerical simulations

Cutting condition	v_c=90 m/min, a_p=0.125, 0.25 mm, a_e=10 mm f=0.05, 0.1 mm/tooth
Tool data	Grooved tool type ANCX090416PDR Sintered carbide insert H10 coated with TiAlN layer of 3 μm thick Tool nose radius r_ε = 1.758 mm Cutting edge radius r_n = 40 μm
Constitutive material models	Johnson-Cook model with defined thermophysical properties of workpiece material (JC)
Simulation models	Three dimensional (3D)

Experiments were carried out on CNC DMU 80P duoBLOCK milling machine equipped with Kistler 9257B piezoelectric dynamometer with 5019B amplifier and NI 6062E (National Instruments), A/D multi-channel board. The visualization of the recorded force signals and their processing was performed using CutPro data acquisition system.

Table 2. Johnson–Cook (JC) material models parameters for Ti6Al4V

Code	A, MPa	B, MPa	n	C	m	ε_0^p 1/s
JC	500	864	0.196	0.0159	0.605	0.0026
Melting temperature			1655 °C			
Young modulus			110 GPa			
Poisson ratio			0.3			
Coefficient of thermal expansion			9,4 10^{-6} 1/K			
Density			4430 kg/ m^{-3}			

3. EXPERIMENTAL RESULTS

The agreement between the simulation model and experimental data was proven based on the cutting power and the specific cutting energy (SCE). Fig. 3 presents several representative changes of the cutting power and SCE as functions of the cutter rotation angle determined for variable depth of cut a_p and feed per tooth f_z. This investigation was performed for finish milling operations when the influence of the cutting edge radius is particularly important. It was observed that the cutting power decreases when the cutter rotation forwards. This effect corresponds strictly with the changes of the uncut chip thickness (UCT). In this case study the down-milling is performed and the maximum and minimum UCT occurs for the rotation angle φ=37° and φ=90° respectively.

The agreement between predicted and experimental data worsened when the depth of cut increases. The simulated values of the cutting power determined for a_p=0.25 mm and f=0.1 mm/tooth overestimate the measurements by 40%. In contrast, a good agreement was documented for a milling operation with a_p=0.125 mm and f=0.05 mm/tooth. In particular, as shown in Fig. 4, the measured cutting power decreases intensively when the rotation angle approaches 75-80°. This effect results from the distinct decrease of the UCT which, in turn, causes visible distributions of chip formation. The same effect but less intensive was observed for simulated power records.

Similar analysis was carried out in terms of the specific (volumetric) cutting energy. It was observed that as the ratio of the uncut chip thickness to the cutting edge radius h/r_n increases, the SCE is reduced from 10-35 GJ/m^3 to 2.5 GJ/m^3. Two distinctive regions can be observed in the Figs. 5 and 6. The first region covers the cases when the uncut chip thickness is much lesser than the cutting edge radius. At this region higher values of the specific cutting energy were determined for simulations and experimental results. This is due to the influence of the ploughing effect as well as the spring back effect causing that chips are not formed [11],[12],[13],[14].

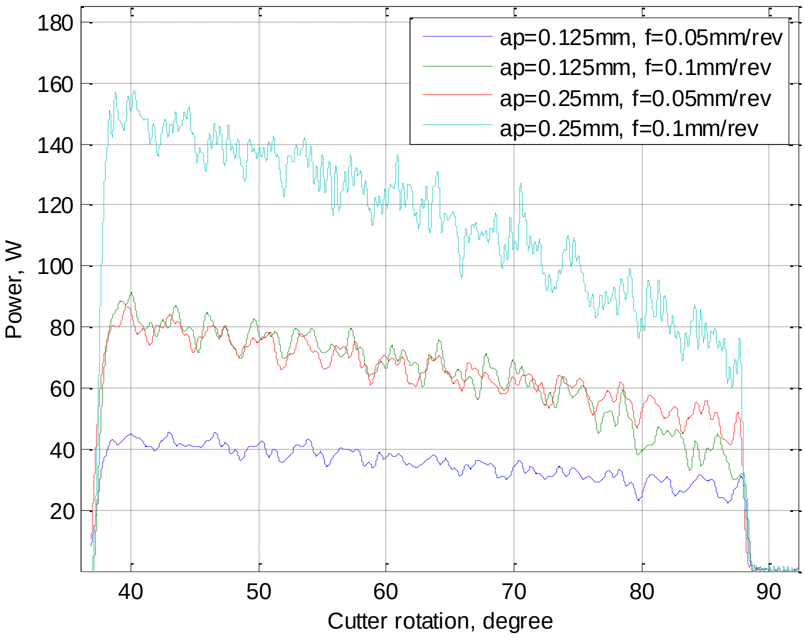

Fig. 3. Power vs. cutter rotation angle based on FEM simulation

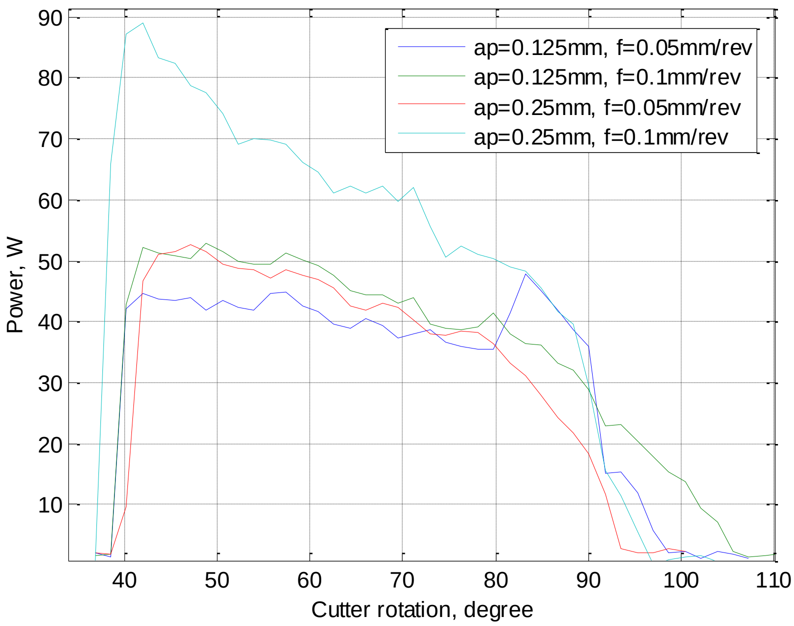

Fig. 4. Power vs. cutter rotation angle based on experimental data

Table 3. Average chip thickness calculated for different depths of cut and feeds

			f_z, mm/tooth / h_m		f_z, mm/tooth / h_m/r_n	
a_p, mm	a_e, mm	κ_r, degree	0.1	0.05	0.1	0.05
0.25	10	27.62	0.021	0.010	0.415	0.207
0.125	10	19.51	0.015	0.008	0.299	0.149

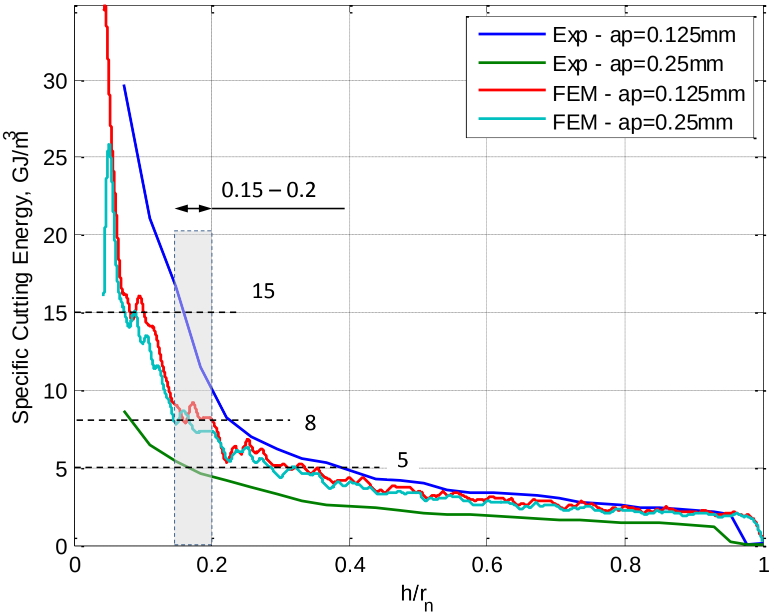

Fig. 5. The influence of size effect on specific cutting energy for FEM and experimental results for feed f=0.05 mm/tooth

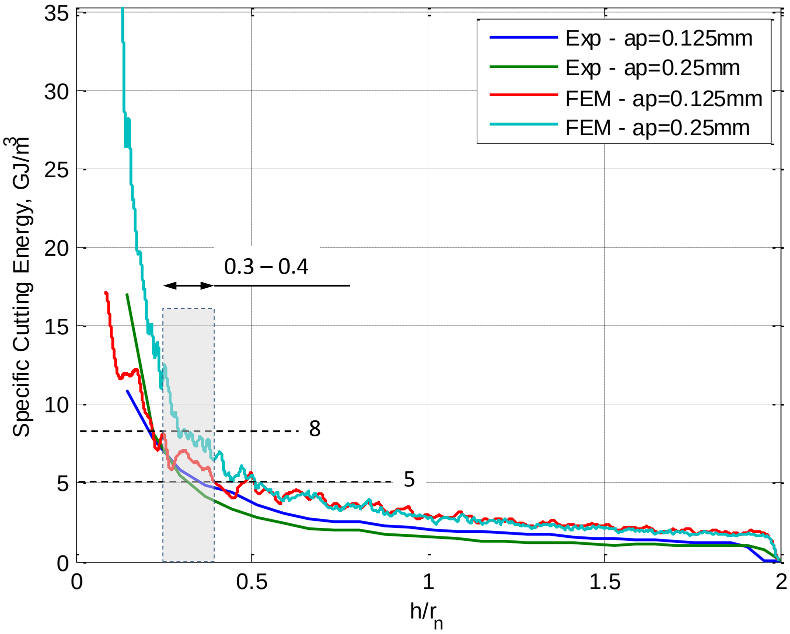

Fig. 6. The influence of size effect on specific cutting energy for FEM and experimental results for feed f=0.1 mm/tooth.

Formula for calculating the average chip thickness for face milling, based on parameters given in Table 3, is given by Equation (1):

$$f_z = h_m \sqrt{\frac{D}{a_e}} \frac{1}{\sin(\kappa)} \Rightarrow h_m = f_z \sin(\kappa) \sqrt{\frac{a_e}{D}} \quad (1)$$

The mean values of the setting angle κ_r (Table 3) were determined graphically by using the CAD model of tool cutting inserts.

For a small feed of f_z =0.05 mm/tooth (Fig.5) the ratio of the UCT to the cutting edge radius h/r_n does not exceed 1. For instance, when $h/r_n < 0.2$, the difference between experimental and simulated data tends to the maximum. The relevant values of the SCE range from 5 to 15 GJ/m^3.

For a higher feed of f_z=0.1 mm/tooth the ratio h/r_n approaches 2 and similarly for smaller values of h/r_n the SCE increases to 35 GJ/m^3. The relevant values of the SCE range from 5 to 8 GJ/m^3. The upper and lower limits are related to experimental and simulated data respectively. It should be noted that for higher values of the ratio h/r_n the changes of the SCE vary in a narrower range of 2-3 GJ/m^3 for both experimental and simulated records. Based on the literature data [15] approximated SCE requirements in cutting operations for titanium alloy vary in the range of 3 to 4.1 GJ/m^3. This fact suggests a good fitting of the parameters of JC constitutive model for face milling operations of Ti6Al4V alloy especially in the terms of the energy analysis.

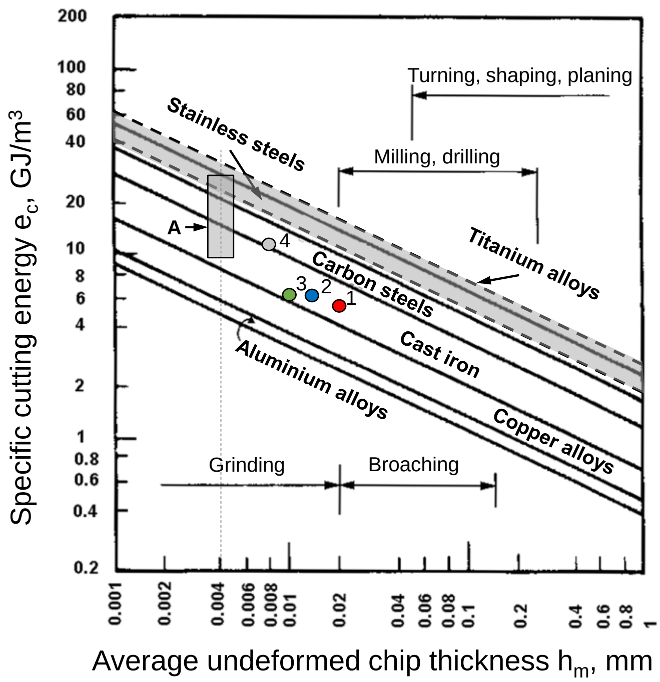

Fig. 7. Influence of uncut chip thickness on the specific cutting energy for variable average chip thickness with data points obtained for the tested cutting conditions. Mean SCE values for: 1 – a_p=0.25 mm f_z=0.1 mm/t, 2 – a_p=0.125 mm f_z=0.1 mm/t, 3 – a_p=0.25mm f_z=0.05 mm/t, 4 – a_p=0.125mm f_z=0.05 mm/t, A – area of SCE for the smallest h≈4 µm [16],[17].

Values of the specific cutting energy determined for milling operations based on experimental and simulations data are specified on the map in Fig. 7. The values of the SCE ranges from 5.5 GJ/m^3 to 12.5 GJ/m^3 depending on the UCT in such away that the lowest value of the SCE corresponds to the higher UCT. In addition, the rectangular area A represents the values of SCE which corresponds to the minimum values of UCT. It should be noted that the maximum value of SCE corresponds to the minimum value of UCT and equals about 4 μm. In addition the dotted upper line represents the values of SCE for the machining of titanium alloys based on refs. [15],[16],[17],[18].

4. CONCLUSIONS

Based on the experimental results and FEM predictions the conclusions are as follows:

- Finish face milling operations are performed with varying power consumption which depends on the rotation angle and, in general, on the cutter engagement conditions.
- In order to minimize the energy consumption, the ratio h/r_n can be used as a variable factor. For higher feed rates the specific cutting energy does not exceed 10 GJ/m^3. In contrast, for lower feed rates the SCE increases distinctly to the values characteristic for grinding operations, i.e above 30 GJ/m^3.

The choice of machining parameters can be based on the analysis of the SCE as function of the $h/r_{n.}$ ratio. Also FEM simulations with the JC constitutive model can support technological selection of machining parameters.

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