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ORIGINAL ARTICLE

Multi-objective optimization of oblique turning operations using finite element model and genetic algorithm

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Abstract Multi-objective optimization of oblique turning operations while machining AISI H13 tool steel has been carried out using developed finite element (FE) model and multi-objective genetic algorithm (MOGA-II). The turning operation is optimized in terms of cutting force and temperature with constraints on required material removal rate and cutting power. The developed FE model is capable to simulate cutting forces, temperature and stress distributions, and chip morphology. The tool is modeled as a rigid body, whereas the workpiece is considered as elastic–thermoplastic with strain rate sensitivity and thermal softening effect. The effects of cutting speed, feed rate, rake angle, and inclination angle are modeled and compared with experimental findings. FE model is run with different parameters with central composite design used to develop a response surface model (RSM). The developed RSM is used as a solver for the MOGA-II. The optimal processing parameters are validated using FE model and experiments.

Keywords Oblique turning · Finite element model · Multi-objective optimization

1 Introduction

Oblique-turning operations differ in several ways with respect to orthogonal turning operations and offer considerable advantages in terms of cutting forces, noise level, and surface quality. Despite majority of the applications require oblique turning operations, most of the research studies are limited to orthogonal turning operations. The main reasons for this are the simplified two-dimensional chip flow and plain strain material formulation. Many researchers used 2D FE model to simulate orthogonal turning operations. These models were quite successful and are computationally inexpensive. However, studies related to modeling of oblique turning are limited, as 3D model simulations were quite expensive, and it was almost impossible to run large set of simulations for an optimization study. However, with the increase in computational power and availability of parallel computing in FE software, 3D simulations are effectively being utilized for real-world machining operations. Although there have been many attempts to model oblique turning operations using 3D FE models, the studies were focused on the accuracy of the models and cutting parameter optimization through FE models has not been considered.

A considerable number of attempts have been made to model oblique cutting using both analytical and numerical modeling. Moufki et al. [1] used an analytical model to model oblique-cutting process. However, the model was limited to steady state material flow, and the deformation in the secondary shear zone was neglected. Fang and Zeng [2] used FEM by incorporating a thermoelastic–plastic material model. The model used a rigid tool, and cutting forces are evaluated by changing the tool inclination angle. The model was not validated experimentally. Zou et al. [3] introduced a new upper bound approach to model oblique cutting. They replaced chip flow angle and apparent coefficient of friction with two new variables based on kinematics and forces in the two deformation zones. The new model was able to predict chip flow angle, and the results were compared with the previously published experimental data. Sedeh et al. [4] used an upper bound approach to model oblique cutting with nose radius tool. They incorporated a new method for calculating the friction area at the chip tool interface. The main assumption employed in the model was that the ratio of tool–chip contact length to shear surface length is the same as that in orthogonal cutting. The chip flow angle calculated with the new approach

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Table 1 Composition and properties workpiece and cutting tool materials

	AISI H13	PCBN
Composition (%)	C 0.32–0.42 Si 0.80 1.20 Cr 4.5–5.5	CBN 65, TiC 35
Density (kg/m^3)	7,800	4,370
Young's modulus (GPa)	211	588
Thermal conductivity (W/m/°C)	37	44
Specific heat (J/Kg/°C)	560	750

found better agreement with the experimental data as compared to the previously published models. Lazoglu and Islam [5] utilized finite difference method (FDM) to calculate temperature fields in oblique turning. In order to solve partial differential equations for oblique cutting using FDM, an elliptical structural grid generation method was presented. Since the resulting system of equations is algebraic, the simulations were found to be much faster as compared to traditional FE methods. The results were compared with experimental findings and the errors were reported to be within 15 %. Li and Shih [6] modeled 3D turning of titanium using commercially available software AdvantEdge®. The effects of cutting speed, depth of cut, and tool cutting edge radius on cutting forces, chip thickness, and maximum temperature were investigated and found to be in good agreement with the experimental observations. Chip segmentation was also analyzed and compared with the experiments. Llanos et al. [7] employed FE model based on Arbitrary Lagrangian Eulerian (ALE) method to model oblique turning operation while machining AISI 4140 using uncoated cemented carbide tools. They performed sensitivity analysis to show the dependencies of cutting tool geometry, cutting conditions, and friction parameters on chip flow angles and cutting forces. A reasonable correlation has been found with the experimental results. The main drawback of such types of models is the incapability to simulate initial chip formation, which is the main driver for further chip growth and stress and temperature distribution.

This study aims to perform multi-objective optimization of oblique turning operation while machining AISI H13 tool steel using poly cubic boron nitride (PCBN) tool inserts with the help of 3D FE model and multi-objective genetic algorithm (MOGA-II). The objective is to minimize main cutting force (force component in the cutting speed direction) and tool–chip interface temperature as both are prime contributors for the machining performance in terms of tool wear and surface integrity of the workpiece. ABAQUS/Explicit is used for developing the 3D FE model and running the simulations. The design of experiments for the FE runs has been carried out using central composite design (CCD) to develop response surface model (RSM). The developed RSM is used as a solver for the optimization search

Table 2 Geometry of work piece and cutting tool

Work piece	
Length	150 mm
Outer diameter	100 mm
Thickness	10 mm
Cutting tool	
Edge chamfer	0.1 mm×25°
Inscribed circle diameter	12.706 mm
Thickness	7.94 mm

Table 3 Selected cutting conditions for the cutting force measurements

S. no.	Rake angle	Inclination angle	Feed rate	Cutting speed
1	−7	0	0.05	200
2	−7	0	0.05	300
3	−7	10	0.25	200
4	−7	10	0.25	300
5	−3	0	0.05	200
6	−3	0	0.05	300
7	−3	10	0.25	200
8	−3	10	0.25	300

Table 4 The Johnson and Cook material flow model's parameters

JC parameters	A (MPa)	B (MPa)	C	*n*	*m*
	674.8	239.2	0.056	0.44	2.7

Table 5 The Johnson and Cook damage law's parameters

JC parameters	D_1	D_2	D_3	D_4	D_5
	−0.8	2.1	−0.5	0.0002	2.7

Table 6 Input variables with their levels for CCD

Levels			
Input variables	0	1	2
Rake angle (α,°)	−3	−5	−7
Inclination angle (λ_s,°)	0	5	10
Feed rate (*f*, mm/rev)	0.05	0.15	0.25
Cutting speed (*V*, m/min)	200	250	300