

## Declaration

I hereby declare that the work presented in this Thesis titled "*Modeling and Control of Geometric Tolerances in End Milling of Thin-walled Components*" submitted to the Indian Institute of Technology Jodhpur in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy, is a bonafide record of the research work carried out under the supervision of *Dr. Kaushal A. Desai*. The contents of this Thesis in full or in parts, have not been submitted to, and will not be submitted by me to, any other Institute or University in India or abroad for the award of any degree or diploma.

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P15ME203



## Certificate

This is to certify that the Thesis titled "*Modeling and Control of Geometric Tolerances in End Milling of Thin-walled Components*", submitted by *Ankit Agarwal (P15ME203)* to the Indian Institute of Technology Jodhpur for the award of the degree of *Doctor of Philosophy*, is a bonafide record of the research work done by him under my supervision. To the best of my knowledge, the contents of this report, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

*Dr. Kaushal A. Desai*  
*Ph.D. Thesis Supervisor*



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*Ankit Agarwal*  
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## List of Symbols

Symbol	Description
$K_T$	Tangential Cutting Constant
$K_R$	Radial Cutting Constant
$K_A$	Axial Cutting Constant
$K_{Tf}$	Flank Edge Tangential Cutting Constant
$K_{Rf}$	Flank Edge Radial Cutting Constant
$K_{Tb}$	Bottom Edge Tangential Cutting Constant
$K_{Rb}$	Bottom Edge Radial Cutting Constant
$F_T$	Tangential Force
$F_R$	Radial Force
$F_A$	Axial Force
$F_F$	Feed Force
$F_N$	Normal Force
$F_X$	Force in X- direction
$F_Y$	Force in Y- direction
$F_X^m$	Experimental Cutting Force in X- direction
$F_Y^m$	Experimental Cutting Force in Y- direction
$F_X^{mf}$	Flank Edge Experimental Cutting Force in X- direction
$F_Y^{mf}$	Flank Edge Experimental Cutting Force in Y- direction
$F_X^{mb}$	Bottom Edge Experimental Cutting Force in X- direction
$F_Y^{mb}$	Bottom Edge Experimental Cutting Force in Y- direction
$F_X^T$	Computational Total Cutting Force in X- direction
$F_Y^T$	Computational Total Cutting Force in Y- direction
$F_X^f$	Computational Flank Cutting Force in X- direction
$F_Y^f$	Computational Flank Cutting Force in Y- direction
$F_X^b$	Computational Bottom Cutting Force in X- direction
$F_Y^b$	Computational Bottom Cutting Force in Y- direction
$dz$	Thickness of Disc Element
$\beta(i, j, k)$	Angular Position of the $k^{th}$ Flute on $j^{th}$ Disk Element at $i^{th}$ Angular Rotation
$\theta_c$	Tooth Spacing Angle of the Cutter
$\theta_h$	Helix Angle of the Cutter
$\theta_{en}$	Engagement Angle
$\theta$	Angle Subtended by $F_N$ with X- axis
$\phi$	Cutter Rotation Angle
$t_c(i, j, k)$	Instantaneous Uncut Chip Thickness
$t_{avg}$	Average Uncut Chip Thickness
$f_{pt}$	Actual Feed per Tooth
$f_a$	Programmed Feed per Tooth
$R_c$	Radius of the Cutter
$R_f$	Final Radius of Curvature
$w(i, j, k)$	Weighting Factor

Symbol	Description
$d_{a1}$	Smaller <i>ADOC</i>
$d_{a2}$	Larger <i>ADOC</i>
$\sigma$	Activation Function
$x_{p,q}$	Output Value of a $q^{th}$ Neuron for $p^{th}$ Layer
$W_{p,q}$	Weight of a $q^{th}$ Neuron for $p^{th}$ Layer
$y$	Predicted Value of ANN Network
$t$	Actual Value of ANN Network
$E$	Error of ANN Network
$\alpha$	Learning Rate
$D_e$	Equivalent Diameter
$n$	Number of Axial Disk
$\delta_T$	Deflection in Tangential Direction
$\delta_N$	Deflection in Normal Direction
$d$	Width of Quad Element in FE
$h$	Height of Quad Element in FE
$acor$	Actual Coordinate
$dcor$	Distorted Coordinate
$RDOC_{act}$	Programmed or Actual <i>RDOC</i>
$RDOC_{rev}$	Corrected <i>RDOC</i>
$a_d$	Arithmetic Mean of Deflections
$A$	Angle with X- axis
$A$	Angle with X- axis
$B$	Angle with Y- axis
$C$	Angle with Z- axis
$D$	Intercept at Z- axis
$PV^f$	Parameter Vector for Flatness
$Flat(PV^f)$	Objective Function for Flatness
$T^t$	Normal Distance from Reference to Bounding Planes
$PV^c$	Parameter Vector for Cylindricity
$Cycl(PV^c)$	Objective Function for Cylindricity
$P_t$	Point-cloud
$P_a$	Position of Point on Axis of Cylinder
$R^t$	Orthogonal Distance between $P_t$ and $P_a$
$m$	Number of Particle in PSO
$w_{max}, w_{min}$	Inertia Weights
$c_1, c_2$	Acceleration Coefficients
$r_1, r_2$	Independently Uniformly Distributed Random Variables
$u$	Number of Iterations in PSO
$LL_{best}$	Individual Local Best
$GL_{best}$	Global Best
$R_L$	<i>RDOC</i> at $L^{th}$ Location along Length of Cut

## List of Abbreviation

Abbreviation	Full form
<i>2D</i>	Two-Dimensional
<i>3D</i>	Three-Dimensional
<i>ADOC</i>	Axial Depth of Cut
<i>ANN</i>	Artificial Neural Network
<i>APDL</i>	ANSYS Parametric Design Language
<i>CAD</i>	Computer Aided Designing
<i>CAM</i>	Computer Aided Manufacturing
<i>CD&amp;T</i>	Coordinate Dimensioning and Tolerancing
<i>CMM</i>	Coordinate Measuring Machine
<i>CNC</i>	Computer Numerical Control
<i>FE</i>	Finite Element
<i>GCS</i>	Global Coordinate System
<i>GD&amp;T</i>	Geometric Dimensioning and Tolerancing
<i>GM</i>	Geometric Tolerance Matrix
<i>LCS</i>	Local Coordinate System
<i>LMC</i>	Least Material Condition
<i>MMC</i>	Maximum Material Condition
<i>PSO</i>	Particle Swarm Optimization
<i>RDOC</i>	Radial Depth of Cut
<i>RM</i>	<i>RDOC</i> Matrix
<i>RNN</i>	Recurrent Neural Network
<i>RRA</i>	Rigidity Regulation Approach
<i>SG</i>	Surface Generation
<i>SOLSH</i>	Solid Shell Element
<i>VM</i>	Velocity Matrix

