



INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI
SHORT ABSTRACT OF THESIS

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Thesis Title: **Numerical and Experimental Studies on Thin-Wall Machining of Aerospace Grade Aluminum Alloy**

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SHORT ABSTRACT

Due to homogeneity and excellent strength-to-weight ratio, monolithic thin-wall components are widely used in aerospace, marine, electronics and automobile industry. Machining of thin-wall parts eliminates the need for different set-ups and processes; however, it consumes a lot of power because of machining of about 90-95% bulk material. Today's manufacturing and tool room industry are striving to reduce the component cost and to improve the product quality in terms of surface finish and dimensional accuracy. To fulfill these requirements it is imperative to focus our research attention on improving the product quality and overall productivity during machining of thin-wall components. The thin-wall parts are always machined on computer numerically controlled (CNC) machines. In spite of using CNC technology, the process of thin-wall machining is not devoid of problems. This is because the process control by CNC is based on idealized geometry and does not take into account the deformation of the parts. As a result, there is a significant deviation between the desired part profile and the manufactured one. Another important aspect related to machining of aluminum thin-wall components is the surface roughness. Aluminum alloys possess a comparatively low modulus of elasticity, which causes the workpiece to spring back. This spring back action often results in deflection and chatter. Chatter affects the material removal (MRR) rate and leads to poor surface finish, part rejection and loss of productivity. Due to the poor stiffness, selecting the optimal machining conditions and parameters is crucial.

In this research work a realistic three-dimensional thermo-mechanical finite element method (FEM) based model was developed to simulate the complex physical interaction of helical cutting tool and workpiece during thin-wall milling of an aerospace grade aluminum alloy. Lagrangian formulation with explicit solution scheme was employed to simulate the interaction between helical milling cutter and

the workpiece. The behavior of the material at high strain, strain rate and the temperature was defined by Johnson-Cook material constitutive model. Johnson-Cook damage law and friction law were used to account for chip separation and contact interaction. Experimental work was carried out to validate the results predicted by the developed 3-D numerical model. It was noted that the milling force component values predicted by the developed model match well with the values that are obtained by experiments. Mean prediction errors for F_x , F_y , F_z , wall deflection and workpiece temperature were found to be 11.61%, 16.38%, 26.1%, 10.02% and 15.61% respectively. Overall a very good agreement between the simulated and experimentally measured responses has been noted which demonstrates the capability of the developed model to predict the process responses accurately.

In view of the requirement of huge computation time (in hundreds of hours) for a 3-D FEM based numerical simulation of thin-wall milling, in the present work, a simple and integrated force-deflection model was developed. The merits of this proposed approach lie in the utilization of unified mechanics based approach and three-dimensional finite element method based simulation together for quicker and accurate prediction the milling force and in-situ wall deflection. Unified mechanics based analytical equations have been thoroughly studied and employed to compute the milling force. Based on these forces, wall deflections have been computed using 3-D finite element method. In this work, the shearing force coefficients those take care of primary shear deformation were derived using established empirical relations. The edge force coefficients those consider the rubbing and ploughing effects were derived by using simple and computationally inexpensive 2-D FEM model. To examine the capability of the proposed approach, four case studies were carried out. Considering all test cases, the mean prediction errors for milling force components F_x , F_y and F_z were noted to be 9.56%, 7.44% and 21.48% respectively. The model was able to predict the wall deflection with a very good accuracy (mean prediction error of 9.3 %). The developed integrated model was found to be far more efficient than the 3-D FEM model. The time duration for prediction of the cutting force and magnitude of wall deflection using the developed integrated model was noted as 40 min in comparison of 344 hrs (average) consumed by the 3-D FEM based thermo-mechanical model. However, the proposed model does not provide the information about the quality of surface machined, chip morphology which is vital in deciding the milling parameters to obtain the desired process performance.

In this research work, systematic experiments have been carried out on thin-wall end milling operation. The experiments were conducted in three phases. Initially, the experiments were carried out to determine the most influential parameters among the milling parameters viz. feed per tooth, spindle speed, axial and radial depth. To carry out this exercise, the performance of milling process was measured in terms of milling force, surface roughness and wall deflection. Radial depth of cut, axial cut depth and feed rate were found to have a significant influence on the performance of thin-wall machining process. However, spindle speed was found to have comparatively less effect on the responses. The levels of these milling parameters were finalized; and these levels were used to carry out further detail experimental investigations.

In the second phase of experiments, investigations into the influence of tool geometry parameters such as tool diameter, helix angle and number of flutes on the performance of the process were carried out. Grey relational analysis (GRA) methodology was utilized to obtain the optimal and influential tool

geometry parameters. Based on the Grey relational rank, tool diameter was found to be highly influencing on the process responses, viz. milling force, surface roughness and wall deflection. GRA suggested that an optimal combination of tool geometry parameters i.e. diameter 8 mm with a helix angle of 45° and 4 flutes achieves the desired process performance. This optimal combination was verified by conducting experiments and it was found that the suggested tool geometry parameters produce a significant improvement in the surface quality of the machined part. An excellent surface finish of 0.401 μm R_a value was obtained. It was also noted that the optimal tool geometry parameters significantly reduce the wall deflection by 6.33%.

In the third phase of work, full factorial experiments were carried out by varying feed per tooth, axial depth of cut, radial depth of cut and tool diameter at three levels. Total 81 experiments were conducted and the process performance in terms of milling force, surface roughness, wall deflection and material removal rate (MRR) were recorded for each experiment. Based on response surface methodology (RSM), systematic studies have been carried out on the perturbation and interaction effects of input milling parameters on the individual performance parameters. Results were studied and the findings were presented with suitable scientific justifications. Based on the RSM, mathematical models for the prediction of individual responses were derived. Further, the predictions by the models were verified by conducting confirmatory experiments. All the models were found to have good prediction capabilities. It was noted that the developed mathematical models predict the responses with good accuracy. The prediction errors (absolute) vary between 0.41 to 16.39%. The mean error for milling force, surface roughness, wall deflection and material removal rate were observed to be 5.9%, 5.5%, 7.9% and 7.8%. Extensive data was generated on the process performance for the chosen milling conditions by carrying out physical experiments. This data was used to derive optimum milling conditions by carrying out multi-objective optimization using the genetic algorithm (GA).

An integrated comprehensive approach for the selection of optimal milling parameters of the helical end milling process to manufacture thin-wall parts was carried out. The approach has the peculiar merit that it takes into account productivity, process efficiency (power consumption) and product quality together. The milling parameters viz. tool diameter, feed per tooth, axial and radial depth of cut were considered in the study. Based on a study of different GA based optimization strategies, non-dominated sorting GA - II (NSGA-II) was selected to solve our optimization problem. Independent objective sub-criteria were defined. Using NSGA-II, Pareto optimal fronts for the roughing and finishing operations were obtained. Exhaustive NSGA-II runs were carried out by varying the number of generations. The Pareto optimal fronts were studied and optimal milling parameters for roughing and finishing operations were suggested. These recommendations were further verified by conducting in-house experiments. The recommendations from the NSGA-II based optimization strategy were found to be very effective in producing quality thin-wall parts of straight as well as curvilinear shapes. It is concluded that good quality surface finish with minimal deflection can be obtained by using an end mill of diameter 8~9 mm and by maintaining the feed, axial and radial depth values at 0.02 mm/z, 8 mm and 0.3125 mm respectively.

The recommended optimum milling conditions were applied to manufacture a 700 μm ultra-thin-wall of curvilinear shape. It was observed that the suggested milling conditions produce an excellent

surface finish of 0.25~0.32 μm (R_a values) and uniform thin-wall (deflection error of 32~41 μm). Thus it is felt that the approach developed in this work provided a very effective tool to the process engineers to choose optimum levels of end milling parameters for enhancing the product quality and process productivity.

