



Experimental and Simulation Analysis of the Turning Process of Inconel 600 Using Al₂O₃-Coated Carbide Tools

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Abstract - This research investigates the impact of machining parameters, During the machining of Inconel 600 workpieces using tungsten carbide tools, both with and without Al₂O₃ coatings. A high-precision infrared thermal camera was employed to measure the temperatures on both the cutting tool and the workpiece, while cutting forces were recorded using a Kistler dynamometer. An L9 orthogonal array experimental design was used to systematically examine the effects of different machining parameters on interface temperatures and cutting forces for both coated and uncoated tools. Additionally, a three-dimensional unsteady-state analysis was carried out using Deform 3D FEA simulate the process of forces and temperature during the turning process. The simulations, which modeled the cutting forces and temperature profiles for both tool types, demonstrated a strong correlation with the experimental results.

Keywords : Interface zone, FEM, Johnson cook, Coated WC Cutting Tool.

1. Introduction

Metal cutting is a manufacturing process used to remove excess material from a workpiece to create components with precise dimensions and desired quality. Among the various metal cutting operations, turning, milling, shaping, boring, and drilling are the most widely used. This study focuses specifically on turning, which serves as a fundamental process for understanding other metal cutting techniques.

Since the 19th century, extensive research has been conducted on metal cutting processes, leading to the development of various methods to enhance their efficiency. Early investigations primarily concentrated on understanding the mechanics of chip formation. Merchant introduced the shear plane concept and developed a mathematical model for the shear angle, based on fundamental principles [1]. Lee and Shaffer used a slip-line model to simulate plastic deformation under plane strain conditions and identified material properties as rigid plastic, applicable primarily to steady-state conditions [2-3]. Trigger, Chao, and Hahn contributed to creating a temperature model for small-scale cutting processes [4]. Bowden and Tabor explored the differences between friction and lubrication in metal cutting [5]. Henriksen

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studied the influence of different rake angles on residual stress in cutting operations [6]. Shirakashi and Usui furthered the application of finite element method (FEM) simulations in metal cutting [7-12]. Shih and Yang introduced a pre-distorted mesh and remeshing technique to reduce simulation time and costs [13]. M'Saoubi and Chandrasekaran investigated the effects of carbide tool microgeometry, including sharp and TiN-coated tools, through experimental methods [14]. J. Tabaki et al. modeled the cutting mechanism in the turning process using the Arbitrary Lagrangian-Eulerian (ALE) formulation [15]. Sushil D et al. measured the temperatures in both coated and uncoated tools during turning operations using a tool-work thermocouple [16].

Finite element analysis (FEA) in these studies often incorporated Johnson-Cook's constitutive equation, which uses material constants for precise simulations. Due to the difficulties in directly measuring temperature at the chip-tool interface, this study suggests employing the inverse heat conduction problem technique to estimate both temperature and heat flux at that interface.

The Lagrangian formulation method is frequently used in metal cutting simulations. In this method, the mesh deforms with the material, updating over time based on material coordinates, which allows simulations to capture the material's history. However, this approach can be computationally intensive, requiring careful management of element distortion to ensure continuous calculations.

2. Experimentation

The work piece used in this study was Inconel 600, and the tool inserts employed are detailed as shown in Table 1.

Table 1. Mechanical and Thermal properties of Workpiece and Tool

Properties	Yong's modulus (E) GPa	Density (ρ) in Kg/m ³	Poisson's Ratio (μ)	Thermal Conductivity (K) in W/mK	Specific Heat (C _p) In J/kg K
Inconel 600	199	7549	0.325	47	431
WC Tool	799	15001	0.21	48	204
Al ₂ O ₃ coated tool	451	14001	0.24	34	401

The experimental setup utilized an HMT Lathe machine with a power rating of 2 kW. The workpiece, with a diameter of 30 mm and a length of 500 mm, was machined using both plain tungsten carbide and Al₂O₃-coated tungsten carbide cutting tool inserts. A tool holder ATJNR 2525-M16 was paired with TNMA 160408 tungsten carbide inserts, which had a negative rake angle of -5°. The machining process was carried out under dry cutting conditions. An infrared thermal camera was employed to measure the temperature in the shear zone using a non-contact method,

providing thermographic data. Cutting forces were recorded with a Kistler dynamometer (Fig1).

For the experimental design, three primary factors were selected. An L9 orthogonal array, based on the Taguchi method, was used to organize the experiments. The factors examined included depth of cut, feed rate, and cutting speed, each tested at three levels: Low, Medium, and High, as detailed in Table 2. This design resulted in nine distinct experiments, each corresponding to a unique combination of the factor levels, as shown in Table 3.



Fig. 1. Experimental setup.

Table 2. Range of Variables

Description	Low	Medium	High
Cutting speed	64	81	96
Feed rate	0.03	0.07	0.22
Depth of cut	0.125	0.25	0.53

Table 3. L9 Orthogonal array Design

Experiment No.	Cutting speed	Feed	Depth of cut
1	65	0.04	0.1
2	65	0.08	0.2
3	65	0.12	0.3
4	80	0.04	0.2

5	80	0.08	0.3
6	80	0.12	0.1
7	95	0.04	0.3
8	95	0.08	0.1
9	95	0.12	0.2

3. Finite Element Modeling and Simulation

Finite element modeling (FEM) is a crucial technique for predicting key machining parameters, such as cutting forces and temperatures. This method requires defining various conditions, including the material properties of both the tool and the workpiece, contact laws, and boundary conditions. Metal cutting processes are treated as transient, nonlinear thermomechanical systems. To improve the accuracy of the simulations and reduce meshing time, the contact interface between the tool and workpiece is meshed with high precision. This technique is especially effective for thermally coupled mechanical applications in metal cutting simulations.

A critical element of successful simulations is the adoption of the Johnson–Cook plasticity model, which establishes a relationship between stress, strain rate, and temperature. This material constitutive model is commonly used in FEM simulations. The Johnson-Cook model accounts for both strain hardening and thermal softening effects. In the model, the equivalent stress (σ) is expressed as a function of equivalent plastic strain (ϵ), material temperature (T), melting temperature (T_m), strain rate ($\dot{\epsilon}^\circ$), and reference temperature (T°). The model also includes constants A and B, which represent yield stress, and parameters C, m, and n, as outlined in equation (1).

$$(A+B(\epsilon^n)) \left[\left(1 + C \ln \frac{\dot{\epsilon}}{\dot{\epsilon}_0} \right) \left(1 - \left(\frac{T-T_0}{T_m-T_0} \right)^m \right) \right] \quad \dots(1)$$

In the simulation, the workpiece is modeled to exhibit a plastic response. Surface-to-surface contact is defined to establish the interfaces between the chip-tool and work-tool. Mesh generation begins by creating elements along the boundaries of both the workpiece and the cutting tool. For the cutting tool, a minimum element size of 0.25 mm is applied. Meshing elements and boundary conditions are specifically assigned at the contact interface between the cutting tool edge and the workpiece. Approximately 15,000 tetrahedral elements are created for the workpiece, while around 20,000 nodes are assigned to the cutting tool. The simulation is performed in 100 steps, with forces and temperature data being recorded at the end of each step. The resulting data is then processed and analyzed using the post-processor module in Deform-3D.

4. Results

The forces and temperatures were obtained from both the experimental setup and simulation models. The data for the uncoated cutting tool are provided in Table 4 and Table 5, while the corresponding results for the Al_2O_3 -coated cutting tool are shown in Table 6 and Table 7. Figures 2 and 3 present a comparison between the simulation and

experimental results for turning operations using the uncoated tungsten carbide (WC) tool, while Figures 4 and 5 show similar comparisons for the Al_2O_3 -coated WC tool.

The results demonstrate that the values predicted by the finite element method (FEM) closely match the experimental data, showing similar trends. For both coated and uncoated tools, the FEM-predicted forces and temperatures are in strong agreement with the experimental observations. Moreover, the Al_2O_3 -coated cutting tool was found to exhibit lower forces during machining compared to the uncoated tool.

Table 4. Resultant Forces using Uncoated Cutting Tool

Exp. No.	Resultant Force (N)		
	Experimental	Simulation	% error
1.	192.01	200.6	4.47
2.	210.7	258.8	6.92
3.	315.6	321.9	1.39
4.	178.9	236.2	6.316
5.	288.5	329	4.055
6.	132.1	152.7	15.59
7.	243.87	280.07	10.79
8.	193.14	227.7	17.89
9.	196.8	273.5	6.85

Table 5. Coated Carbide tool - Temperature distribution

Exp. No.	Temperature °C		
	Experimental	Simulation	% error
1.	113.78	126	10.74
2.	160	200	25
3.	177.52	186	4.77
4.	265.11	320	20.7
5.	265.14	386	45.5
6.	169.17	186	9.94
7.	264.92	382	44.19
8.	172.26	200	16.1
9.	264.9	296	11.7

Table 6. Resultant Forces using Al_2O_3 Coated Carbide

Exp. No.	Resultant force (N)		
	Experimental	Simulation	% error
1.	42.65	89.2	52.18
2.	52.34	70.5	25.4
3.	161.87	211.4	23.4
4.	83.42	103.04	19.01
5.	137.32	162.2	15

6.	130.32	151.5	13
7.	123.89	143.5	13
8.	95.52	102.7	6
9.	139.36	146.8	5

Table 7. Al₂O₃ Coated Carbide - Temperature distribution

Exp. No.	Temperature °C		
	Experimental	Simulation	% error
1.	110.2	120	8.1
2.	151.2	162	6.6
3.	162.6	172	5.4
4.	147.73	156	5.3
5.	176.73	178	0.9
6.	166.2	172	3.3
7.	149.6	153	2.2
8.	128.84	132	2.3
9.	139.8	146	4.2

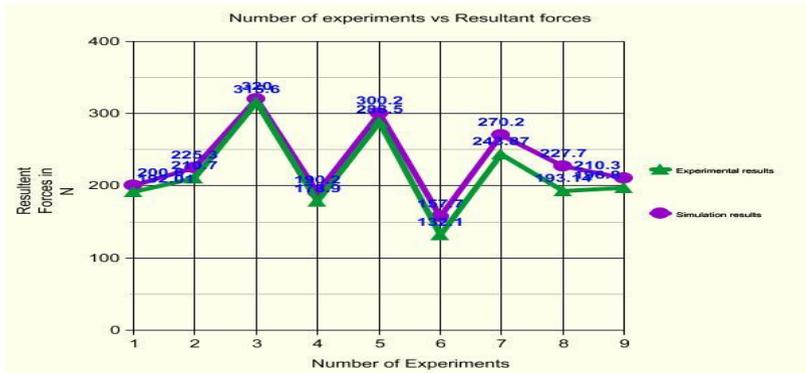


Fig. 2. Comparison of resultant force values obtained from experimental and simulation results for the uncoated tool.

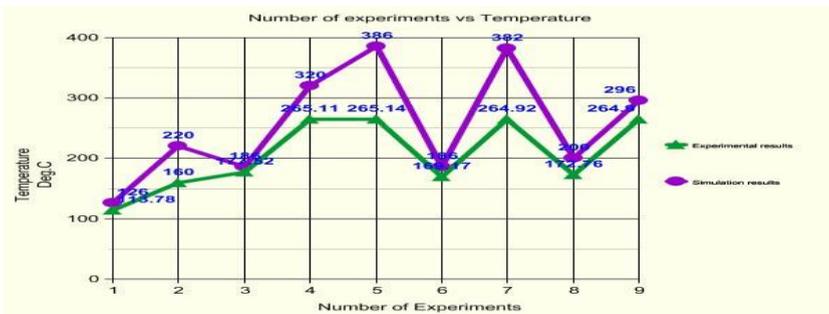


Fig. 3. Comparison of temperature values from experimental and simulation results for the uncoated tool.

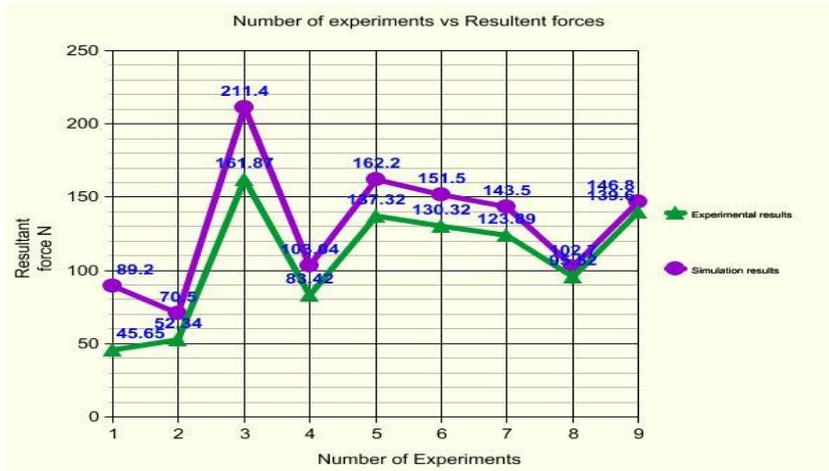


Fig. 4. Comparison of resultant force values from experimental and simulation results for the coated tool.

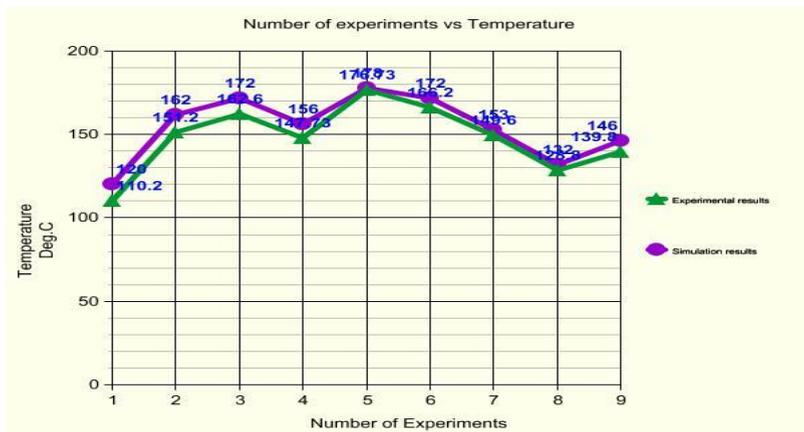


Fig. 5. Comparison of temperature values from experimental and simulation results for the coated tool.

5. Conclusions

The finite element method, utilizing DEFORM 3D software, has proven to be an effective approach for analyzing trends, enabling the estimation of cutting forces and temperatures in metal cutting processes. This method considers various design factors, including machining parameters. The simulation results for cutting forces and temperatures closely aligned with the experimental data. Furthermore, it was observed that the use of Al₂O₃ -coated tungsten carbide (WC) tools led to a reduction in cutting forces, with significantly lower values compared to those recorded with uncoated tools.

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