

Simulation-based optimization of machining forces in turning Inconel 718 employing the Johnson–Cook model

Fitim Zeqiri¹ 

¹ Faculty of Mechanical and Computer Engineering, University “Isa Boletini” Mitrovica, Mitrovica, Kosovo
E-mail: fitim.zeqiri@umib.net

ABSTRACT

This study investigates the influence of cutting parameters on cutting forces during the turning of Inconel 718 using the finite element method (FEM). Numerical simulations were carried out with Deform 3D (V6.1) and validated against established theoretical models. The Johnson–Cook constitutive model was applied to describe the material behavior under high strain rates and elevated temperatures, while process optimization was performed using the Taguchi design of experiments (DOE) in Minitab 17. The results demonstrate that cutting speed, feed rate, and depth of cut significantly affect cutting forces in all three directions (F_x , F_y , F_z). Specifically, increasing cutting speed reduces cutting forces, whereas higher feed rates and depths of cut increase them. Furthermore, tool geometry – particularly tool nose radius– was found to influence tangential and radial forces while reducing axial forces. The proposed numerical model shows strong agreement with published experimental data, confirming the accuracy of FEM in predicting cutting forces during the machining of Inconel 718. These findings provide valuable insights for optimizing turning parameters, improving tool life, and ensuring machining efficiency in the processing of difficult-to-cut superalloys.

Keywords: Inconel 718, finite element modelling, cutting force, Taguchi design.

INTRODUCTION

The numerical analysis of cutting forces in turning processes is of critical importance, as these forces govern tool wear, machining accuracy, and surface quality. During turning, a variety of complex physical phenomena occur in the cutting zone, where the workpiece material interacts with the cutting insert. These interactions generate stresses, deformations, and heat, making it necessary to apply both theoretical and experimental approaches to predict cutting forces accurately.

Workpieces are manufactured from a wide range of materials, and each requires the determination of optimal cutting parameters and cutting tool geometries. These parameters directly influence:

- the surface roughness of machined parts,
- the magnitude of cutting forces,
- tool wear and tool life,
- cutting temperature,
- chip formation and removal rate,

- vibrations during machining, and
- the overall stability of the cutting process.

Finite element analysis (FEA) has emerged as a powerful tool for predicting cutting forces and simulating chip formation. By considering the effect of individual parameters, FEA enables realistic, predictive solutions that complement experimental studies. In this research, the finite element model implemented in Deform 3D (V6.1) was used to simulate the turning of Inconel 718, allowing calculation of the cutting force components in three directions as well as detailed modeling of the chip formation process.

The investigation of cutting forces is a key factor in machining because these forces directly determine surface finish, tool wear rate, tool life, and the power required for cutting. Numerical analysis allows optimization of machining parameters, providing the best possible trade-off between machining efficiency and tool longevity.

During the cutting process, the rake and clearance angles of the tool act on the workpiece material through contact surfaces, generating resistance to chip flow. The resulting cutting forces originate from the material's resistance to plastic deformation, which includes shear, bending, and fracture, as well as frictional forces at the tool–chip interface. These forces and the corresponding moments define many of the machining process characteristics, including cutting temperature, machine tool load, tool stability, machining accuracy, and cutting power consumption. To determine cutting forces, two principal methods are generally applied:

1. Analytical methods, which model chip deformation and tool geometry mathematically. Although useful for qualitative understanding, they often rely on assumptions and unknown parameters, limiting their practical application.
2. Experimental methods, which involve direct measurement of cutting forces under controlled conditions. While accurate, they can be expensive and time-consuming.

A hybrid analytical–experimental (regression-based) approach combines the strengths of both methods. Using planned experiments and regression analysis, empirical models of cutting forces can be developed for practical use. Such models are essential for optimizing cutting processes, designing tools and machines, and enabling adaptive machining systems. The accurate prediction of cutting forces in the machining of Inconel 718 has been a critical focus in recent research due to the material's high strength, work hardening, and poor thermal conductivity. Several studies have employed finite element analysis (FEA) in combination with the Johnson–Cook constitutive model to simulate cutting forces and optimize machining parameters.

Gurusamy and Muthukrishnan (2023) investigated the selection of Johnson–Cook model parameters specifically for Inconel 718, highlighting the sensitivity of predicted cutting forces to the accurate calibration of material constants. They emphasized that small deviations in strain rate or thermal softening parameters could lead to significant differences in simulated force values, indicating the importance of precise parameter determination for reliable FEM results.

Jafarian and Tawakoli (2014) conducted finite element simulations of machining Inconel 718 using the Johnson–Cook model, demonstrating its capability to capture the nonlinear behavior of

the alloy under high strain rates and temperatures. Their results confirmed that FEA could accurately predict cutting force trends and chip formation, providing a valuable tool for process optimization without extensive experimental trials.

Nasralla et al. (2018) combined FEM with optimization techniques to estimate cutting forces during turning of Inconel 718. Using regression and Taguchi-based design of experiments, they showed that cutting speed, feed rate, and depth of cut had distinct and quantifiable effects on axial, radial, and tangential forces, which could be exploited to enhance tool life and machining efficiency.

Paturi and Reddy (2021) further explored the influence of machining parameters on Inconel 718 using finite element simulations. Their study confirmed that feed rate and depth of cut were dominant factors in increasing cutting forces, whereas cutting speed influenced thermal softening effects and resulted in reduced force magnitudes, consistent with prior experimental and numerical findings.

Qiu and Zhang (2019) performed sensitivity analysis on Johnson–Cook material constants to assess their effect on cutting force predictions in Inconel 718 turning. The study revealed that the constants governing strain rate sensitivity and thermal softening were most critical, emphasizing the necessity of accurate experimental calibration of the Johnson–Cook parameters to ensure reliable FEM simulations.

Vasant and Soni (2018) validated finite element simulations of cutting forces with experimental measurements, demonstrating strong agreement between predicted and measured axial, radial, and tangential forces. Their work confirmed that FEM could serve as a practical and efficient alternative to direct experimentation for process planning and optimization. Wang and Zhang (2013) proposed a modified Johnson–Cook model to better capture the dynamic behavior of Inconel 718 at elevated temperatures and high strain rates. Their modifications improved the predictive accuracy of cutting forces and chip formation characteristics in simulations, suggesting that tailored material models enhance the fidelity of numerical machining studies.

MATERIAL PROPERTIES OF INCONEL 718

Inconel 718 is a nickel–chromium-based superalloy widely used in aerospace, energy, and

high-performance engineering applications due to its excellent mechanical strength, corrosion resistance, and high-temperature stability.

According to international standards, the alloy is designated as UNS N07718/W with material number 2.4668. Its uniform microstructure, high hardness, and good machinability make it a suitable material for experimental and numerical investigations of cutting processes. The chemical composition of Inconel 718 is provided in Table 1.

The high strength of Inconel 718 is derived from the combined effects of niobium and molybdenum additions in the nickel–chromium matrix, eliminating the need for additional heat treatments. This unique composition also provides exceptional resistance to oxidation, carburization, and corrosion under elevated temperature conditions.

NUMERICAL ANALYSIS SETUP

The numerical analysis of cutting forces was conducted using Deform 3D V6.1, a specialized FEA software for metal cutting simulations. The software employs both SI and Imperial unit systems, allowing flexibility in modeling.

The turning process was simulated following the same technological sequence as in experimental machining, ensuring consistency between numerical and practical conditions. The main steps of the analysis included:

1. Selection of the workpiece material (Inconel 718).

2. Definition of the turning process type.
3. Selection of the cutting tool insert and its holder.
4. Specification of machining parameters (cutting speed, feed rate, depth of cut).
5. Definition of boundary and environmental conditions for the simulation.
6. Generation of the finite element mesh for both workpiece and cutting tool.

The workpiece and cutting tool insert (CNMG-type) were discretized using mesh modeling, enabling precise simulation of stress distribution and chip formation. The mesh density was optimized to balance computational efficiency with solution accuracy.

Johnson–Cook constitutive model

The Johnson–Cook (J–C) model was adopted to describe the flow stress of Inconel 718 under conditions of high strain, strain rate, and temperature. The constitutive equation is given by:

$$\bar{\sigma} = [A + B \cdot \bar{\epsilon}^n] \cdot \left[1 + C \cdot \ln \left(\frac{\dot{\bar{\epsilon}}}{\dot{\bar{\epsilon}}_0} \right) \right] \cdot \left[1 - \left(\frac{T - T_{room}}{T_{melt} - T_{room}} \right)^m \right] \quad (1)$$

The Johnson–Cook model accounts for strain hardening, strain rate sensitivity, and thermal softening. The constant values for Inconel 718, taken from literature, are summarized in Table 2.

The J–C model is widely used in machining simulations due to its robustness and adaptability for numerical solutions. For Inconel 718, it provides a reliable description of plastic deformation behavior under extreme cutting conditions.

Taguchi design of experiments

To investigate the effect of machining parameters, the Taguchi method was employed using a 3-level L9 orthogonal array. Three parameters were varied: cutting speed (v), feed rate (s) and depth of cut (a). The chosen levels for each parameter are given in Table 3.

The experimental design ensures that the combined effect of these parameters on cutting forces can be efficiently studied with minimal simulation runs while maintaining statistical accuracy.

Table 1. Chemical composition of Inconel 718

Element	Weight %
Nickel (plus Cobalt)	50.55–55.00
Chromium	17.00–21.00
Niobium	4.75–5.50
Molybdenum	2.80–3.30
Titanium	0.65–1.15
Aluminum	0.20–0.80
Cobalt	≤ 1.00
Carbon	≤ 0.08
Manganese	≤ 0.35
Silicon	≤ 0.35
Phosphorus	≤ 0.015
Sulfur	≤ 0.015
Boron	≤ 0.006
Copper	≤ 0.30

Table 2. Johnson–Cook model constants for Inconel 718

A (MPa)	B (MPa)	n	C	m	$\dot{\epsilon}_o$ (1/s)	Troom (°C)	Tmelt (°C)
450	1700	0.65	0.017	1.3	0.001	20	1300

RESULTS AND DISCUSSION

The cutting force simulations were carried out in Deform 3D V6.1 using the Taguchi L9 experimental design. Cutting forces were predicted along the three orthogonal axes (Fx, Fy, Fz), representing axial, radial, and tangential force components. The numerical results provide insight into how cutting parameters – cutting speed (v), feed rate (s), and depth of cut (a) – affect the machining process of Inconel 718.

Cutting force simulation

The predicted cutting forces from the FEM analysis for all nine Taguchi experiments are summarized in Table 4. The results clearly indicate strong dependence of the cutting forces on the feed rate and depth of cut, while the cutting speed primarily influences the overall magnitude of forces (Figure 1).

Regression analysis

Regression models were developed in Minitab 17 to quantify the effect of process parameters on cutting forces. The following regression equations were obtained:

- For axial force Fx:

$$Fx = 9322 - 13.74v - 1674s - 96a \quad (2)$$

- For radial force Fy:

$$Fy = 3165 - 1.67v - 941s - 377a \quad (3)$$

- For tangential force Fz:

$$Fz = 9960 - 18.8v + 1880s + 2750a \quad (4)$$

The regression analysis shows that:

- Fx is significantly reduced by increasing cutting speed and slightly affected by feed rate and depth of cut.
- Fy is less sensitive to cutting parameters, indicating it is more stable across conditions.
- Fz is strongly influenced by both feed rate and depth of cut, which are the dominant contributors to tangential force.

Statistical evaluation

The statistical significance of parameters was analyzed through ANOVA. For axial force Fx, the regression model achieved an R² of 79.8%, indicating good predictive accuracy. Cutting speed was the most significant factor (p = 0.011), whereas feed rate and depth of cut showed weaker significance.

For radial (Fy) and tangential (Fz) forces, the models achieved lower R² values, suggesting greater variability in simulation results due to nonlinear effects and chip formation instabilities.

Main effects of machining parameters

The Taguchi main effects plots illustrate the influence of machining parameters on cutting forces:

- Cutting speed (v): Increasing cutting speed results in a reduction of cutting forces, primarily due to thermal softening of the material at higher temperatures.
- Feed rate (s): A higher feed rate significantly increases cutting forces, especially Fz, as more material is removed per revolution.
- Depth of cut (a): Larger depths of cut also increase cutting forces, with the strongest effect observed in tangential force Fz.

These findings are consistent with reported experimental results in the machining of nickel-based superalloys.

Key observations

The numerical results highlight the following key observations:

1. Cutting speed is the most effective parameter for reducing cutting forces, confirming that

Table 3. Cutting parameters for Taguchi DOE

Parameter	Level 1	Level 2	Level 3
Cutting speed, v (m/min)	350	475	500
Feed rate, s (mm/rev)	0.05	0.375	0.700
Depth of cut, a (mm)	0.50	1.25	2.00

Table 4. Predicted cutting forces using Deform 3D (Taguchi L9 design)

Cutting speed v (m/min)	Feed rate, s (mm/rev)	Depth of cut a (mm)	F _x (N)	F _y (N)	F _z (N)
350	0.050	0.50	2185.20	1103.47	5113.42
350	0.375	1.25	2544.86	1471.99	7298.43
350	0.700	2.00	2544.85	1471.01	8663.19
475	0.050	1.25	2400.13	732.07	6633.77
475	0.375	2.00	3421.47	3357.79	2562.46
475	0.700	0.50	2176.70	1329.42	4699.67
500	0.050	2.00	4338.37	1122.18	4241.76
500	0.375	0.50	3310.60	952.51	14523.32
500	0.700	1.25	1727.68	3594.28	3268.89

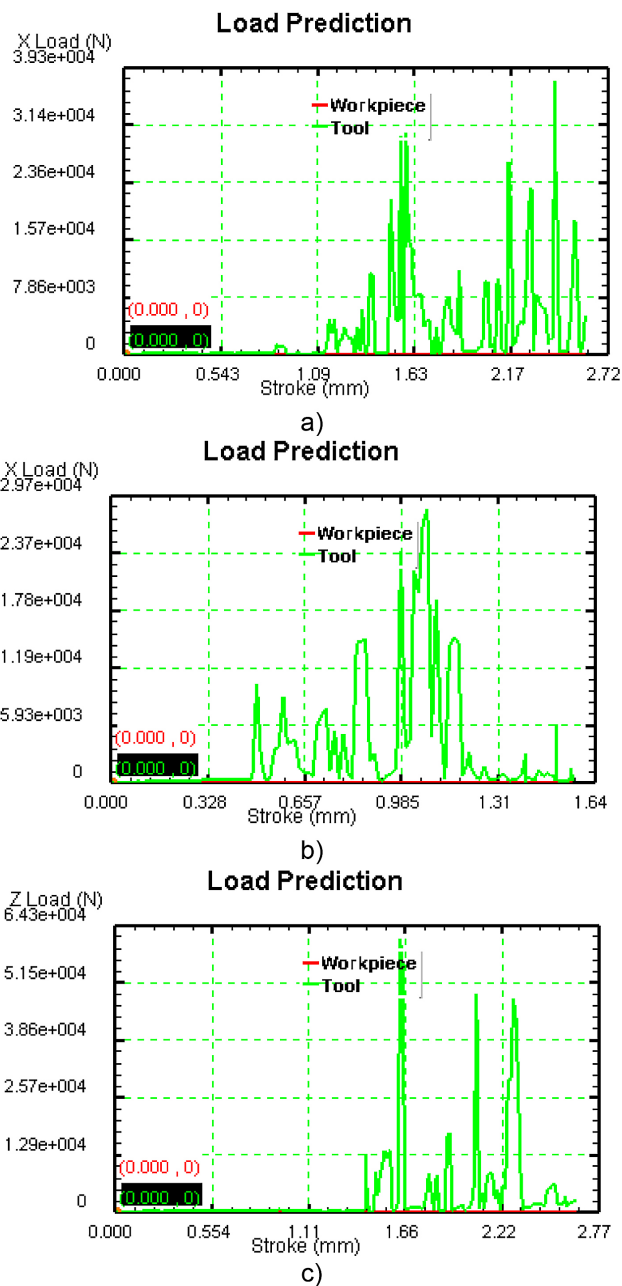


Figure 1. a) Cutting Force Simulation F_x=4338.37 N, b) Cutting Force Simulation F_y=3594.28 N, c) Cutting Force Simulation F_z= 14523.32 N

higher speeds promote material softening and reduce tool-chip contact stresses.

2. Feed rate and depth of cut exert strong positive influence on cutting forces, particularly tangential force (F_z), which directly relates to cutting power requirements.
3. Radial forces (F_y) are less sensitive to parameter variations, which explains their more stable behavior in machining simulations.
4. The regression models confirm that predictive equations can be developed for estimating cutting forces in Inconel 718, although nonlinearity and thermal effects introduce variability.
5. The FEM simulations provide results comparable to experimental studies, supporting the validity of the Johnson-Cook material model and the Taguchi optimization approach.

CONCLUSIONS

This study investigated the influence of cutting parameters on cutting forces during the turning of Inconel 718 using finite element modeling in Deform 3D V6.1. The Johnson–Cook constitutive model was implemented to capture the thermo-mechanical behavior of the alloy under high strain rates and elevated temperatures. A Taguchi L9 experimental design was applied to systematically study the effects of cutting speed, feed rate, and depth of cut. The main findings can be summarized as follows:

1. Cutting speed has a strong inverse relationship with cutting forces. As speed increases, forces decrease due to thermal softening of the work-piece material.
2. Feed rate significantly increases cutting forces, particularly the tangential component (F_z), which is directly related to cutting power consumption.
3. Depth of cut also increases forces, with the greatest effect on tangential force (F_z) and moderate influence on axial (F_x) and radial (F_y) forces.
4. The tool nose radius influences tangential and radial forces, which increase with larger radii, while axial forces tend to decrease.
5. Regression models developed in Minitab 17 successfully described the relationships

between cutting parameters and cutting forces. The model for axial force (F_x) achieved the highest predictive accuracy ($R^2 = 79.8\%$), confirming the reliability of the simulation results.

6. The numerical results from FEM analysis are in good agreement with reported experimental data from the literature, demonstrating the validity of the proposed modeling approach.

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