

Parametric Optimization of CNC Milling of Aluminium 7075 Using the TOPSIS Multi-Criteria Decision-Making Method

Rahul Mali

Pimpri Chinchwad College of Engineering

Swaraj Raut

Pimpri Chinchwad College of Engineering

Sahil Powar

Pimpri Chinchwad College of Engineering

Shantanu Ranbhare

Pimpri Chinchwad College of Engineering

Atharva Wankar

Pimpri Chinchwad College of Engineering

Rohit Zende

zenderohit@gmail.com

Rajarambapu Institute of Technology

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Abstract

This study presents a multi-response optimization of CNC milling parameters for Aluminium 7075 alloy using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). A Taguchi L27 orthogonal array was employed to investigate the effects of spindle speed, feed rate, and depth of cut under dry milling conditions. Cutting forces were measured using a KISTLER 9257B piezoelectric dynamometer with a National Instruments cDAQ-9174 data-acquisition system, while spindle power was monitored using a Hioki PW3198 power-quality analyser. Specific Cutting Energy (SCE) and resultant cutting force were considered non-beneficial responses and assigned equal weights in the primary TOPSIS analysis. The results indicate that increasing feed rate generally reduced SCE but increased resultant cutting force, while greater depth of cut increased cutting-force requirements. Higher spindle speed generally reduced resultant cutting force. The optimum combination was identified as 3700 rpm spindle speed, 450 mm/min feed rate, and 0.8 mm depth of cut, achieving a TOPSIS closeness coefficient of 0.858 for equal weighting. Sensitivity analysis confirmed this parameter combination as a recurrent optimum under different response weightings. The findings demonstrate the effectiveness of TOPSIS for balancing energy efficiency and cutting-force reduction in Aluminium 7075 milling.

1. Introduction

Machining remains an important manufacturing route for producing components with controlled geometry, dimensional accuracy and surface integrity. Milling is particularly versatile because a rotating multi-point cutter can generate flat surfaces, slots, grooves, contours and complex three-dimensional features [1, 2]. CNC milling further improves repeatability and process control through programmed spindle speed, feed rate and tool motion. Contemporary manufacturing, however, requires more than dimensional accuracy and productivity; energy consumption, cutting-force control, process stability, tool life and sustainable operation are increasingly important considerations [3–5]. Milling performance depends on cutting speed or spindle speed, feed rate, depth of cut, tool geometry, tool material, workpiece material and machining environment [6, 7]. Among these variables, spindle speed, feed rate and depth of cut are dominant controllable parameters because they influence cutting forces, material-removal behaviour, power demand, surface quality, tool loading and process stability [8–10]. Conventional parameter selection based mainly on operator experience and trial-and-error can produce inconsistent results and may not provide a satisfactory compromise among competing machining objectives [11, 12].

Aluminium 7075 is a high-strength aluminium alloy used in aerospace structures, defence components and high-performance engineering applications. Its combination of low density and high mechanical strength makes it attractive where weight reduction and structural performance are important [13, 14]. Nevertheless, milling of Aluminium 7075 can involve increased cutting resistance, tool wear, thermal effects, vibration and surface-quality deterioration when machining parameters are poorly selected. Systematic parameter optimization is therefore relevant to both productivity and energy-efficient manufacturing [15–17]. Specific Cutting Energy (SCE) provides an energy-efficiency measure by relating

machining energy to the volume of material removed. Lower SCE indicates that less energy is required per unit volume of material removal. In practical machining, however, minimum energy is not the only objective: a parameter combination that minimizes SCE may simultaneously increase cutting force or compromise process stability. This creates a multi-objective decision problem in which responses must be considered together [7, 18, 19]. Multi-Criteria Decision-Making (MCDM) methods such as TOPSIS, Grey Relational Analysis, VIKOR, AHP, MOORA and WASPAS have therefore been applied to machining optimization. TOPSIS ranks alternatives according to their relative distance from a positive ideal solution and a negative ideal solution. Its principal advantage in the present application is that several responses with different units can be normalized, weighted and combined into a single closeness coefficient [20–22].

Previous research has established that feed rate and cutting conditions strongly affect surface roughness and milling performance, while mechanistic and analytical studies have developed approaches for predicting milling forces [23–25]. Studies on machining energy have shown that process parameters can change energy consumption even when comparable amounts of material are removed. Research on specific cutting energy has further emphasized the importance of considering material-removal rate rather than evaluating electrical power alone [26–28]. Recent work has applied MCDM methods, including TOPSIS, to machining parameter selection and multi-objective optimization. The literature indicates a continuing need to integrate force and energy criteria within a single optimization framework [29–31].

The present study addresses this requirement by treating SCE and resultant cutting force as simultaneous non-beneficial responses. The approach combines experimental measurements, Taguchi design and TOPSIS ranking, with sensitivity analysis used to examine whether the selected optimum persists when the relative importance of the two responses is changed. The present work applies TOPSIS to the simultaneous minimization of SCE and resultant cutting force during dry CNC milling of Aluminium 7075. The objectives of the study are to: (i) experimentally investigate Aluminium 7075 milling under different spindle speeds, feed rates and depths of cut; (ii) measure machining-force responses; (iii) determine SCE from machining-energy data; (iv) examine the influence of machining parameters on SCE and resultant cutting force; (v) design the experimental programme using a Taguchi L27 orthogonal array; (vi) apply TOPSIS for multi-response optimization; and (vii) examine the robustness of the selected optimum using sensitivity analysis.

2. Materials and Methods

2.1 Experimental setup

Experiments were conducted in a machining and manufacturing laboratory at Visvesvaraya National Institute of Technology (VNIT), Nagpur. Figure 1 shows the experimental Setup (VNIT Nagpur). The experimental system consisted of a CNC vertical machining centre, a KISTLER piezoelectric dynamometer, a force/data-acquisition system, a power-quality analyser, a surface-roughness tester,

carbide milling cutter and a hydraulic tool holder. The workpiece was rigidly clamped on the dynamometer, which was mounted on the machine table. Cutting-force signals were acquired during machining, while electrical power associated with the spindle motor was monitored independently. All tests were performed under dry machining conditions [32–35]. Figure 2 shows experimental methodology and measurement sequence.

2.2 Workpiece material

Figure 3 shows aluminium 7075 alloy workpiece used for the milling experiments. Aluminium 7075 alloy was selected because of its extensive use in aerospace, defence and automotive applications requiring high strength with low weight [16, 36, 37]. Workpiece specimens were prepared to permit repeated milling tests under the prescribed parameter combinations. Prior to machining, the workpiece surfaces were cleaned and aligned to provide consistent clamping and contact conditions [37–39].

2.3 CNC machine tool

Figure 4 shows CNC Machine Used (ASKAR MICRONS). The experiments were performed on a CNC vertical machining centre (ASKAR MICRONS). CNC machining was selected to maintain consistent programmed conditions over all trials. The machine was operated as a three-axis system under dry end-milling/slot-milling conditions [14, 40, 41]. Table 1 depicts CNC vertical machining centre specifications.

Table 1
CNC vertical machining centre specifications

Parameter	Specification
Machine type	CNC Vertical Machining Centre
Machining operation	End milling
Control system	CNC controlled
Number of axes	3-axis
Work material	Aluminium 7075
Machining environment	Dry machining
Operation type	Slot milling / end milling

2.4 Tool holder

Figure 5 shows Tool Holder {BT40 Hydraulic Chuck (25mm)}. A BT40 hydraulic chuck with a 25 mm clamping diameter was used. The hydraulic holder was selected to provide rigid and repeatable tool clamping and to reduce the influence of tool runout and vibration on force measurements [42, 43]. Figure 6 shows tool used (Walter M4132 Cylindrical Modular Milling Cutter). Table 2 depicts tool-holder specifications.

Table 2
Tool-holder specifications

Parameter	Specification
Taper standard	BT40
Clamping diameter	25 mm
Actuation method	Lateral screw
Maximum speed	20,000 + rpm
Clamping force	High
Coolant supply	AD/B

2.5 Cutting tool and insert

Figure 7 shows tool Insert (Tungsten Carbide). The cutter was a Walter M4132 cylindrical modular milling cutter fitted with Walter SPHT09T308-G88 WK10 carbide inserts. The tungsten-carbide insert was uncoated and had a square geometry, G88 chip-breaker geometry, an 11° rake angle, an 8 mm nose radius and a nominal 4 mm thickness. The selected tooling was intended to provide stable cutting and repeatable engagement during the experimental programme [44]. Table 3 depicts cutting-tool insert specifications.

Table 3
Cutting-tool insert specifications

Parameter	Specification
Cutter	Walter M4132 cylindrical modular milling cutter
Insert	SPHT09T308-G88 WK10
Insert material	Tungsten carbide
Shape	Square
Coating	Uncoated
Chip breaker	G88
Rake angle	11°
Nose radius	8 mm
Insert thickness	4 mm
Cutting direction	Right hand
Mounting style	Screw held
Inscribed circle	9.525 mm

2.6 Cutting-force measurement

Figure 8 shows dynamometer (KISTLER). Cutting forces were measured using a KISTLER Type 9257B piezoelectric dynamometer. The dynamometer provides three-component force measurement in the X, Y and Z directions. The workpiece was clamped directly on the dynamometer to minimize vibration and measurement errors. The recorded force signals were transferred to the data-acquisition system for subsequent processing [45]. Table 4 depicts dynamometer specifications.

Table 4
Dynamometer specifications

Parameter	Specification
Model	KISTLER 9257B
Load capacity	10 kN
Clamping area	100 × 170 mm
Natural frequency	5 kHz
Sensitivity (Fx, Fy)	5 pC/N

2.7 Data acquisition

Figure 9 shows DAQ System (NI cDAQ-9174). A National Instruments NI cDAQ-9174 data-acquisition chassis was used to acquire and store the dynamometer signals. LabVIEW was used for monitoring and recording the force signals. The stated acquisition frequency was 12,000 Hz, enabling the transient force variation associated with milling to be captured [46, 47]. Table 5 depicts data-acquisition specifications.

Table 5
Data-acquisition specifications

Parameter	Specification
Model	NI cDAQ-9174
Type	Eight-slot USB chassis
Sampling frequency	12,000 Hz
Software	LabVIEW

2.8 Power measurement

Figure 10 shows power Quality Analyser (Hioki). A Hioki PW3198 power-quality analyser was connected to the spindle-motor circuit to monitor electrical current and power during machining. The current measurement range of 500 mA to 5 kA, a sampling frequency of 200 kHz and current-sensor accuracy of ± 0.2% of reading ± 0.1% of full scale. The recorded data were subsequently processed using Hioki PQA-HiView software [48, 49]. Table 6 depicts power-quality analyser specifications.

Table 6
Power-quality analyser specifications

Parameter	Specification
Instrument	Hioki PW3198
Current range	500 mA–5 kA
Sampling frequency	200 kHz
Current-sensor accuracy	$\pm 0.2\%$ rdg $\pm 0.1\%$ f.s.

2.9 Design of experiments

A Taguchi L27 orthogonal array was used because three machining factors were investigated at three levels. The factors were spindle speed, feed rate and depth of cut. The 27-run design provides all combinations required for the selected three-level experimental programme while maintaining a structured design suitable for comparative analysis [50]. Table 7 depicts input machining factors and Table 8 depicts selected machining-parameter levels.

Table 7
Input machining factors

Factor	Parameter	Unit
A	Spindle speed	rpm
B	Feed rate	mm/min
C	Depth of cut	mm

Table 8
Selected machining-parameter levels

Level	Spindle speed (rpm)	Feed rate (mm/min)	Depth of cut (mm)
1	1600	150	0.8
2	2650	300	1.6
3	3700	450	2.4

2.10 Response calculations

Table 9 depicts Taguchi L27 experimental matrix. Resultant cutting force was determined from the measured force components. For the principal analysis, the resultant force was treated as a non-beneficial response because lower force is associated with reduced tool loading and improved machining stability. Specific Cutting Energy was treated as a non-beneficial response because lower energy per unit material removal represents greater energy efficiency. The SCE in J/mm³ and resultant force in N. The TOPSIS procedure comprised construction of the decision matrix, vector normalization, application of response weights, identification of positive and negative ideal solutions, calculation of

Euclidean distances and calculation of the closeness coefficient. Equal weights of 0.50 and 0.50 were initially assigned to SCE and resultant force. For non-beneficial criteria, the minimum weighted normalized value was used to define the positive ideal solution and the maximum value the negative ideal solution. The alternative with the largest closeness coefficient was selected as the preferred machining condition [30, 51].

Table 9
Taguchi L27 experimental matrix

Run	Speed (rpm)	Feed (mm/min)	DOC (mm)
1	1600	150	0.8
2	1600	300	0.8
3	1600	450	0.8
4	2650	150	0.8
5	2650	300	0.8
6	2650	450	0.8
7	3700	150	0.8
8	3700	300	0.8
9	3700	450	0.8
10	1600	150	1.6
11	1600	300	1.6
12	1600	450	1.6
13	2650	150	1.6
14	2650	300	1.6
15	2650	450	1.6
16	3700	150	1.6
17	3700	300	1.6
18	3700	450	1.6
19	1600	150	2.4
20	1600	300	2.4
21	1600	450	2.4
22	2650	150	2.4
23	2650	300	2.4
24	2650	450	2.4
25	3700	150	2.4
26	3700	300	2.4
27	3700	450	2.4

3. TOPSIS Optimization

TOPSIS was selected because SCE and resultant cutting force are measured in different units and can respond differently to changes in machining parameters. The method converts the two responses to dimensionless normalized values and then combines them according to their assigned weights. The closeness coefficient expresses the relative position of each experimental alternative between the positive and negative ideal solutions.

For each experimental alternative i and criterion j , the vector-normalized value was obtained as [52]

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \dots \dots \dots (1)$$

The weighted normalized value was then obtained as $v_{ij} = w_j \times r_{ij}$, with $w_1 = 0.50$ for SCE and $w_2 = 0.50$ for resultant force in the primary analysis. The positive ideal solution consisted of the minimum values of both non-beneficial criteria, whereas the negative ideal solution consisted of the corresponding maximum values. Euclidean distances from the positive and negative ideals were calculated, and the closeness coefficient was obtained as [53]

$$C_i = \frac{S_i^-}{S_i^- + S_i^+} \dots \dots \dots (2)$$

A higher C_i therefore indicates a more desirable combined response.

4. Results and Discussion

4.1 Effect of spindle speed

Table 10 shows experimental response values. The experimental results indicate that spindle speed strongly affects resultant cutting force. At a fixed feed rate and depth of cut, increasing spindle speed generally reduced the measured resultant force. For example, at the 150 mm/min feed condition and 0.8 mm depth of cut, the reported resultant force decreased from 64.54 N at 1600 rpm to 38.90 N at 3700 rpm. The reduction is consistent that higher spindle speed can reduce the interaction time associated with each cutting engagement and facilitate chip formation. The response of SCE was less monotonic: the reported values indicate that SCE can increase with spindle speed at low feed rate, whereas higher feed rates produce lower SCE values.

Table 10
Experimental response values

Run	Speed	Feed	DOC	SCE (J/mm ³)	Resultant force (N)
1	1600	150	1.6	2.884	133.3042
2	1600	300	1.6	1.812	174.0115
3	1600	450	1.6	1.455	226.4597
4	2650	150	1.6	4.291	101.0445
5	2650	300	1.6	2.515	130.4186
6	2650	450	1.6	1.924	152.4106
7	3700	150	1.6	5.698	84.1724
8	3700	300	1.6	3.219	113.8991
9	3700	450	1.6	2.393	104.4844
10	1600	150	0.8	2.884	64.5368
11	1600	300	0.8	1.812	88.0909
12	1600	450	0.8	1.455	110.4219
13	2650	150	0.8	4.291	47.634
14	2650	300	0.8	2.515	67.0075
15	2650	450	0.8	1.924	84.4038
16	3700	150	0.8	5.698	38.8973
17	3700	300	0.8	3.219	56.5862
18	3700	450	0.8	2.393	65.1153
19	1600	150	2.4	2.884	173.3667
20	1600	300	2.4	1.812	237.2003
21	1600	450	2.4	1.455	331.4408
22	2650	150	2.4	4.291	125.6025
23	2650	300	2.4	2.515	170.8011
24	2650	450	2.4	1.924	214.021
25	3700	150	2.4	5.698	125.1759
26	3700	300	2.4	3.219	154.3826
27	3700	450	2.4	2.393	163.8933

4.2 Effect of feed rate

Feed rate produced the clearest trade-off between force and energy. At 1600 rpm and 1.6 mm condition, resultant force increased from 133.30 N at 150 mm/min to 174.01 N at 300 mm/min and 226.46 N at 450 mm/min. The increase is associated with greater chip load and material removal per unit time. In contrast, SCE decreased from 2.884 J/mm³ at 150 mm/min to 1.812 J/mm³ at 300 mm/min and 1.455 J/mm³ at 450 mm/min under the same reported condition. Thus, increasing feed rate improves the energy-per-volume metric while increasing instantaneous cutting force. Table 11 depicts effect of feed rate on resultant force.

Table 11
Effect of feed rate on resultant force

Feed rate (mm/min)	Resultant force (N)
150	133.304
300	174.011
450	226.46

4.3 Effect of depth of cut

Depth of cut had a substantial influence on resultant cutting force. Increasing the engaged depth increases the material-tool contact and consequently raises the force requirement. For example, at 2650 rpm and 300 mm/min, the 67.01 N at 0.8 mm and 142.00 N at 1.6 mm in its discussion. The broader response matrix also shows markedly larger forces for the 2.4 mm condition. Lower depth of cut is therefore favourable for force reduction within the tested range.

4.4 Specific Cutting Energy

SCE decreased as feed rate increased. The minimum SCE reported in the experimental response matrix is 1.455 J/mm³, occurring at 1600 rpm, 450 mm/min and the condition labelled 1.6 mm in the response table. The maximum SCE of 5.698 J/mm³ in the response matrix for 3700 rpm, 150 mm/min and the condition labelled 1.6 mm. These values indicate that the energy required per unit volume can be substantially affected by feed rate and machining conditions. Because SCE and resultant force do not improve simultaneously for every parameter combination, a multi-response method is appropriate.

4.5 Primary TOPSIS results

Table 12 depicts TOPSIS closeness coefficients and ranking for the 50:50 weighting case. The highest closeness coefficient was 0.8584 for Run 18, corresponding to 3700 rpm spindle speed, 450 mm/min feed rate and 0.8 mm depth of cut in the experimental matrix. Run 15 (2650 rpm, 450 mm/min, 0.8 mm) ranked second with $C_i = 0.8571$, while Run 11 ranked third with $C_i = 0.8536$. The close coefficients of the leading alternatives show that the optimum represents a balance between the low force associated with

high spindle speed and the low SCE associated with high feed rate. Table 13 depicts optimum machining condition from the primary TOPSIS analysis

Table 12
TOPSIS closeness coefficients and ranking
for the 50:50 weighting case

Run	Closeness coefficient, Ci	Rank
1	0.6729	13
2	0.6369	14
3	0.5425	24
4	0.6227	16
5	0.7058	9
6	0.6838	12
7	0.5513	22
8	0.6894	10
9	0.7768	8
10	0.8074	5
11	0.8536	3
12	0.8051	6
13	0.6892	11
14	0.8427	4
15	0.8571	2
16	0.5987	18
17	0.7812	7
18	0.8584	1
19	0.5774	21
20	0.5047	25
21	0.4013	27
22	0.5787	20
23	0.6075	17
24	0.5437	23
25	0.4906	26
26	0.5987	19

Run	Closeness coefficient, Ci	Rank
27	0.6315	15

Table 13
Optimum machining condition from the primary TOPSIS analysis

Parameter	Selected optimum	TOPSIS indicator
Spindle speed	3700 rpm	Highest-ranked combination
Feed rate	450 mm/min	Highest tested feed level
Depth of cut	0.8 mm	Lowest tested depth
Closeness coefficient	0.8584	Rank 1

4.6 Sensitivity analysis

To examine the influence of decision-maker preference, the TOPSIS procedure using SCE/resultant-force weightings of 40:60, 30:70, 20:80 and 10:90 in addition to the 50:50 case. Run 18 (3700 rpm, 450 mm/min, 0.8 mm) remained the top-ranked alternative in the 40:60, 30:70 and 50:50 cases and was also among the highest-performing alternatives for the other weighting scenarios. The sensitivity analysis therefore supports the selection of the high-speed, high-feed, low-depth combination as a robust compromise between the two non-beneficial responses. Table 14 depicts sensitivity-analysis summary based on the reported TOPSIS calculations.

Table 14
Sensitivity-analysis summary based on the reported TOPSIS calculations

Weighting (SCE : force)	Best/selected run	Ci reported for Run 18
50 : 50	18	0.8584
40 : 60	18	0.8796
30 : 70	18	0.8951
20 : 80	18	0.9046
10 : 90	18	0.9092

The results demonstrate a clear multi-response trade-off. Increasing feed rate raises resultant force because of increased chip load, but simultaneously lowers SCE because the material-removal rate increases relative to energy demand. Increasing spindle speed generally lowers resultant force in the tested range, although SCE is not necessarily minimized at the highest speed for low-feed conditions. Increasing depth of cut increases cutting force and therefore reduces the attractiveness of the larger depth when force reduction is an objective. TOPSIS integrates these competing trends and identifies a parameter combination that provides a balanced response rather than optimizing either force or energy independently. The selected condition 3700 rpm, 450 mm/min and 0.8 mm, therefore represents a multi-

response compromise within the tested experimental domain. It should be interpreted as the optimum for the investigated machine, tool, workpiece, dry-cutting environment and parameter range rather than as a universal optimum for all Aluminium 7075 milling operations.

Conclusions

A systematic experimental and TOPSIS-based approach was used to optimize dry CNC milling of Aluminium 7075. The principal conclusions are as follows:

1. Spindle speed, feed rate and depth of cut substantially affected the resultant cutting force and Specific Cutting Energy.
2. Increasing feed rate increased resultant cutting force but reduced SCE, demonstrating the conflict between force minimization and energy-per-volume minimization.
3. Increasing depth of cut increased the cutting-force requirement; the lowest tested depth was therefore favourable for force reduction.
4. Higher spindle speed generally reduced resultant cutting force under the tested conditions.
5. For the primary 50:50 weighting of SCE and resultant force, Run 18 gave the highest TOPSIS closeness coefficient, $C_i = 0.8584$.
6. The selected machining condition was 3700 rpm spindle speed, 450 mm/min feed rate and 0.8 mm depth of cut.
7. Sensitivity analysis with alternative response weightings showed that the selected high-speed/high-feed/low-depth combination remained a recurrent optimum, supporting the robustness of the decision.
8. The methodology provides a practical framework for balancing machining force and energy efficiency and can be extended by including additional responses such as tool wear, material-removal rate, temperature, vibration, surface roughness and machining cost.

The present optimization is limited to the tested parameter ranges, the selected Aluminium 7075 workpiece, the specified carbide tool, the CNC machine and dry machining conditions. Future studies should include tool wear, surface roughness, material-removal rate, machining temperature, vibration and total power consumption as additional criteria. Comparisons among dry machining, minimum-quantity lubrication, flood cooling and cryogenic cooling could further clarify the sustainability implications. Hybrid optimization combining TOPSIS with Taguchi analysis, response-surface methods, artificial intelligence or genetic algorithms could also be explored. Sensor-based monitoring and adaptive control may enable real-time adjustment of machining parameters in Industry 4.0 environments.

Declarations

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Author Contribution

Rahul A. Mali: Conceptualization, data curation, investigation, methodology, and writing—original draft; Swaraj Raut: Conceptualization, investigation, methodology, review and editing; Sahil Powar: Conceptualization, investigation, methodology, review and editing; Shantanu Ranbhare: Conceptualization, investigation, methodology, review and editing; Atharva Wankar: Conceptualization, investigation, methodology, review and editing; Rohit Zende: Conceptualization, investigation, methodology, review and editing, Supervision.

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Data Availability Statement

The data that support the findings of this study will be made available on request from the corresponding author.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures



Figure 1

Experimental Setup (VNIT Nagpur)

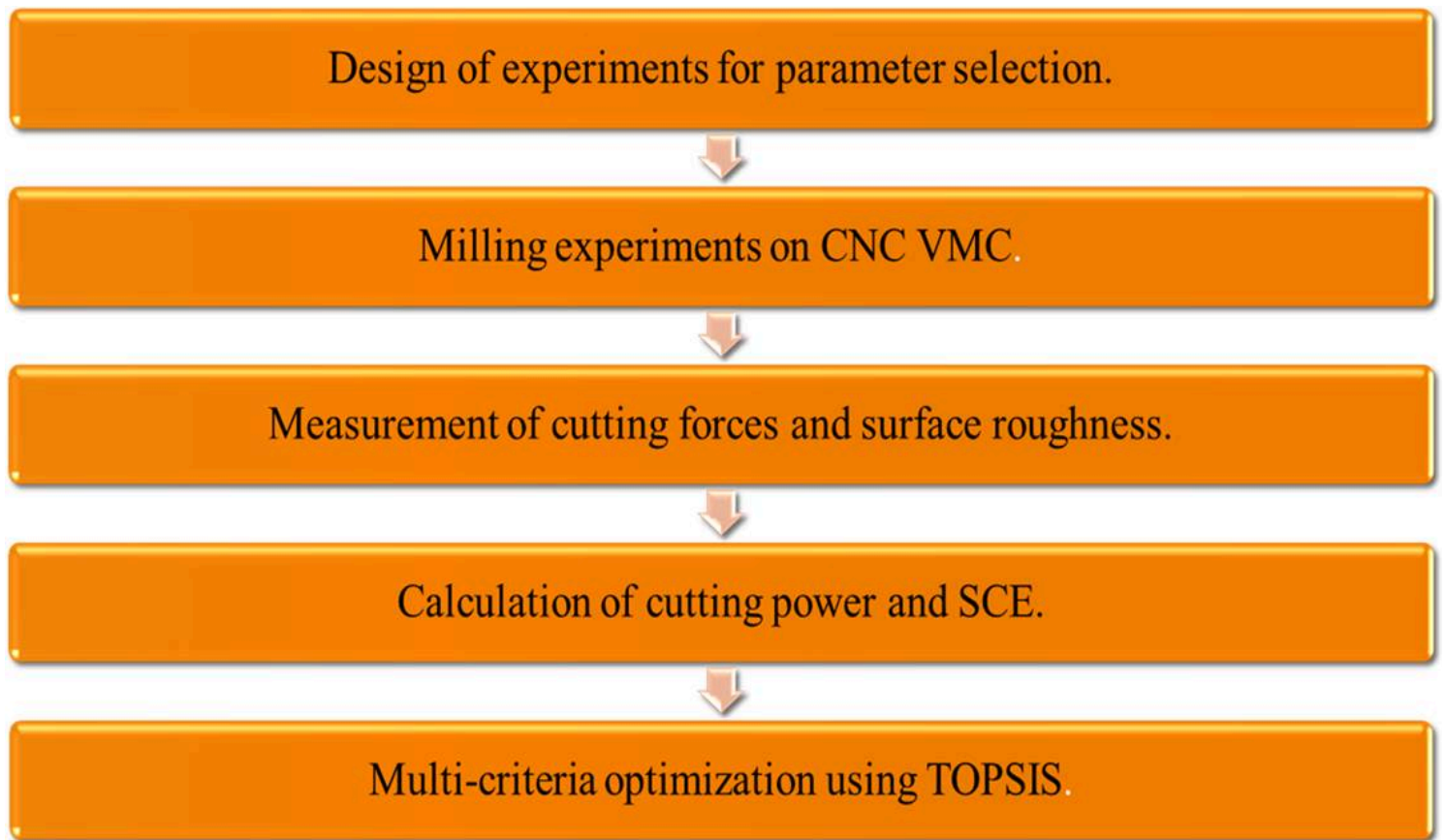


Figure 2

Experimental methodology and measurement sequence

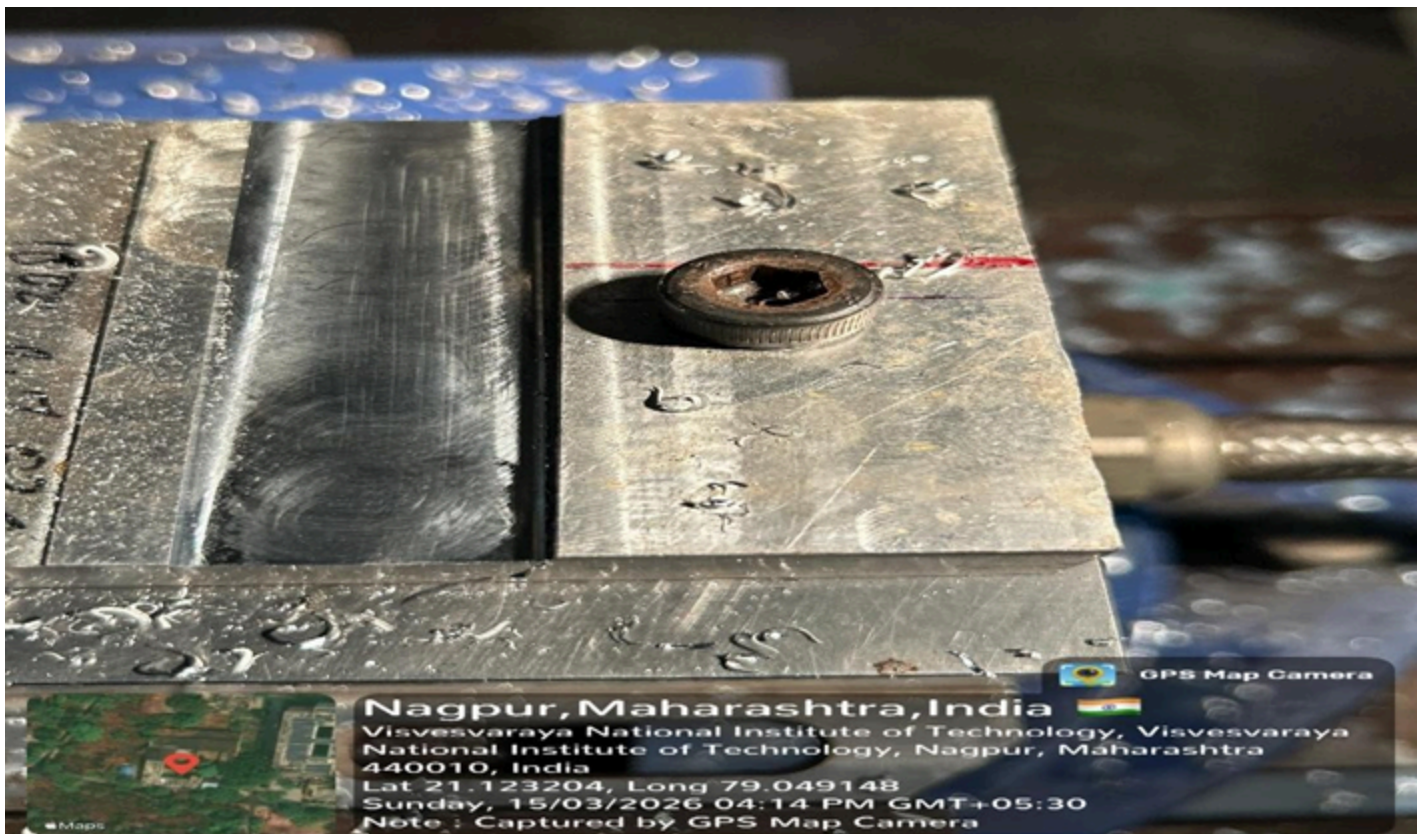


Figure 3

Aluminium 7075 alloy workpiece used for the milling experiments



Figure 4

CNC Machine Used (ASKAR MICRONS)



Figure 5

Tool Holder {BT40 Hydraulic Chuck (25mm)}



Figure 6

Tool Used (Walter M4132 Cylindrical Modular Milling Cutter)



Figure 6

Tool Used (Walter M4132 Cylindrical Modular Milling Cutter)



Figure 7

Tool Insert (Tungsten Carbide)



Figure 7

Tool Insert (Tungsten Carbide)



Figure 8

Dynamometer (KISTLER)



Figure 9



Figure 10

Power Quality Analyser (Hioki)