

# Comparative Study of Rotational and Longitudinal Turning: Energy Efficiency and Surface Roughness in Machining Normalized Medium-Carbon Steel

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*This study compares rotational and longitudinal turning during the machining of normalized medium-carbon steel. The aim is to evaluate differences in energy efficiency and surface quality. Three tools were tested: two rotational turning tools with 30° and 45° inclination angles and a conventional longitudinal turning tool. Thirty-six cutting experiments were performed while varying depth of cut, feed, and cutting speed. Cutting forces were measured in three directions and used to calculate specific cutting forces and total mechanical work. Surface roughness was evaluated using arithmetical mean roughness and maximum peak-to-valley height parameters. The results show that rotational turning, particularly with a 30° inclination, reduces specific cutting forces and enables lower energy consumption at comparable productivity. It also provides better surface finish at medium and high feeds. Longitudinal turning generated acceptable energy levels but produced significantly rougher surfaces. The findings highlight the role of tool inclination in improving energy-surface-quality interactions.*

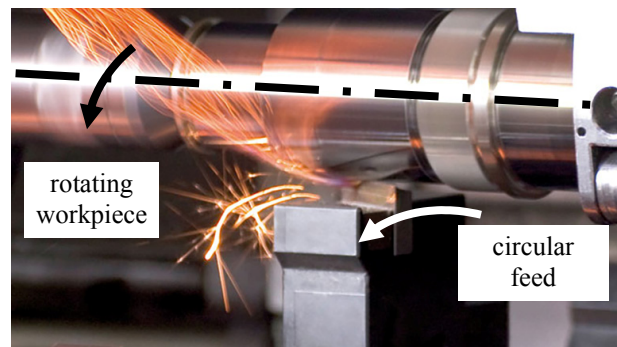
**Keywords:** Energy efficiency, Machining, Medium-carbon steel, Rotational turning, Specific cutting force, Surface roughness.

## 1. INTRODUCTION

In the field of manufacturing engineering, the demand for energy-efficient and high-quality machining processes has intensified significantly in recent years [1,2]. This growing importance is largely driven by economic and environmental concerns, paired with the increasing need for precision and consistency in the production of mechanical components. Among the various machining operations, turning remains one of the most fundamental and widely applied processes for shaping rotationally symmetric parts such as shafts, bushings, and bearing components [3,4]. Despite its apparent developed state, the turning process continues to be an active area of research due to its critical role in productivity, surface integrity, and overall process sustainability [5,6].

Traditionally, turning operations are performed using a longitudinal feed strategy, where the cutting tool moves parallel to the axis of the rotating workpiece [7]. This method has been the pillar of cylindrical machining and is well-documented in both industrial practice and scientific literature. However, recent advancements in tooling concepts and kinematic alternatives have led to the development of non-traditional turning strategies [8,9], among which rotational turning (also referred to as tangential turning with circular feed movement) has

gained increasing attention [10-12]. In rotational turning, the cutting edge is oriented at an angle to the workpiece axis and a circular secondary feeding movement is applied [13,14], introducing a fundamentally different engagement between the cutting edge and the material.



**Figure 1. Rotational turning [14]**

This alternative approach offers unique advantages in chip formation, force distribution, and tool wear behaviour, and it has potential for specific applications where the application of conventional methods are limited. The motivation for exploring rotational turning lies in its ability to address challenges that are difficult to overcome with longitudinal turning. These include tool vibration, heat concentration, and unfavourable force component distributions, which can lead to early tool wear, poor surface finish, and excessive energy consumption. The introduction of an inclination angle in rotational turning modifies the chip load distribution and contact geometry, which can influence both the cutting forces and the

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resulting surface topography [15,16]. Consequently, this modified kinematics can enable higher productivity under certain conditions, especially when combined with optimized cutting parameters.

Despite the promising nature of rotational turning, there remains a lack of comprehensive studies that directly compare its performance with conventional longitudinal turning under controlled and repeatable experimental conditions. This is particularly true for studies that jointly evaluate energy efficiency and surface quality, which are critical performance indicators in modern manufacturing [17,18]. Most existing literature tends to focus on either force analysis or surface integrity in isolation, often without considering the broader context of process sustainability and machinability. Moreover, the influence of tool inclination angle – a key parameter in rotational turning – on energy consumption and surface roughness is still not fully understood, especially when machining common engineering materials such as medium-carbon steels. Medium-carbon steels, including normalized C45 steel, are widely used in the manufacturing of automotive, structural, and machinery components due to their good balance of strength, machinability, and cost-effectiveness [19,20]. Although not regarded as a high-performance alloy, C45 represents a class of workpiece materials that is highly relevant in industry and thus serves as a meaningful subject for comparative machining studies [21–23]. The machining of normalized C45 presents moderate cutting resistance, making it suitable for evaluating process-induced differences in energy demand and surface finish across various tool geometries and feed strategies.

To quantify energy efficiency, cutting forces should be measured using a high-precision dynamometer [24,25]. From the force components, the mechanical work done during cutting could be calculated, which serves as a direct indicator of energy consumption in the material removal process. In addition, the specific cutting force values could be calculated to normalize the data and enable meaningful comparisons across different setups. These parameters are particularly useful in evaluating the effectiveness of each turning strategy in terms of material removal efficiency [26–28]. Beyond evaluating machining forces and energy consumption, cutting-force measurements also provide essential input for analysing the dynamic behaviour of turning tools. Studies have demonstrated that measured cutting forces can be integrated into analytical or numerical models to estimate tool displacement and vibration response during turning operations [29,30]. Cutting-force data are equally valuable in stability investigations, where they support the development and validation models used to study chatter behaviour, forced vibration, and the performance of advanced tool-holder structures [31,32]. These applications highlight that high-quality force measurements are not only important for analysing cutting mechanics but also play a central role in understanding and improving the dynamic stability and vibration resistance of turning processes.

In parallel with force and energy measurements, surface roughness is often characterized using two widely accepted parameters: arithmetical mean roughness and maximum height of the roughness profile. These

values provide complementary insights into the quality of the machined surfaces. The analysis of these parameters assists the identification of surface finish trends associated with different tool geometries and cutting conditions [33–35]. The wider literature also shows that surface roughness evaluation plays a central role in many machining studies, even when the work materials or machining strategies differ from the present work. For example, investigations have shown that both cutting tool geometry and process parameters strongly influence surface roughness and dimensional accuracy, with high cutting speeds and low feed rates leading to improved surface quality [36,37]. Other studies have focused on the prediction of surface roughness using data-driven approaches, where image processing combined with machine learning techniques has achieved high correlation levels when estimating roughness parameter values [38,39]. Furthermore, studies have confirmed that surface roughness is strongly dependent on feed rate, which often emerges as the dominant parameter influencing machinability, while excessive depth of cut may lead to undesirable increases in cutting force and degradation in surface finish [40–42]. These examples underline the broad applicability of roughness-based evaluation across machining research and support the need for detailed surface characterization in comparative studies such as this.

The present study addresses these gaps by conducting a systematic comparative investigation of rotational and longitudinal turning, focusing on the energy efficiency and surface roughness characteristics achieved when machining normalized medium-carbon steel. Three tool configurations are used: a standard longitudinal turning tool and two rotational turning tools with inclination angles of 30° and 45°, respectively. The experiments cover a range of cutting parameters, including different feeds, depths of cut, and cutting speeds, allowing for an evaluation of process performance under varied conditions. The findings from this study are expected to contribute both to academic understanding and practical process optimization. The comparative evaluation of cutting forces and surface roughness under the two turning strategies will show the conditions under which rotational turning can be a viable or even preferable alternative to longitudinal turning. In addition, the results of the role of tool inclination angle in rotational turning can inform tool design and process planning decisions, particularly in high-feed or energy-sensitive applications.

Although several recent studies have examined rotational turning individually, most of them focus either on force prediction or on surface quality alone [12,15,16,43,44], without integrating energy efficiency into the evaluation. Moreover, many of the available investigations are limited to narrow ranges of feeds or tool geometries, which does not reflect the higher feed rates increasingly demanded in modern production. Comparative studies for different turning procedures are particularly uncommon, and very few provide a simultaneous analysis of cutting forces, specific cutting forces, total work input, and detailed surface roughness metrics under identical conditions [45–47]. These gaps in the literature highlight the need for a comprehensive assess-

ment of how tool inclination and cutting parameters jointly influence both energy use and surface quality. The present study addresses these shortcomings by providing a complete experimental comparison and by quantifying the energy-to-surface-quality relationship.

Modern manufacturing increasingly requires machining processes that simultaneously improve energy efficiency and surface integrity while maintaining high productivity [48,49]. Traditional longitudinal turning often struggles to meet these requirements at elevated feeds due to increased cutting forces and weakened surface quality [50,51]. These limitations motivated the present research, which aims to clarify whether rotational turning (with its characteristic inclined cutting edge and altered tool-workpiece kinematics) can offer a more energy-efficient alternative with better surface quality. The central objective of this study is therefore to provide a systematic, experimentally verified comparison between rotational and longitudinal turning in terms of cutting forces, specific cutting forces, total mechanical work, and the resulting surface roughness. In conclusion, this study is a timely and necessary contribution to the evolving development on sustainable and high-performance machining. By evaluating rotational turning in direct comparison with traditional longitudinal turning, and by doing so through an energy- and surface-focused analysis, the work aligns with current industry priorities and scientific interests.

## 2. MATERIALS AND METHODS

An experimental procedure was employed for the comparative analysis of rotational and conventional turning processes. To evaluate the cutting forces in rotational turning, a previously developed force measurement system was utilized [5]. The current section details the experimental setup, including the machine tool, workpiece material, cutting tools, and applied cutting parameters. In addition, the methods used for cutting force measurement, energy calculation, and surface roughness evaluation are presented.

### 2.1 Experimental Setup

The experimental setup is shown in Figure 2. The cutting experiments were carried out on a Perfect-Jet MCV-M8 machining centre (with high-speed spindle and adequate rigidity to ensure consistent cutting conditions).

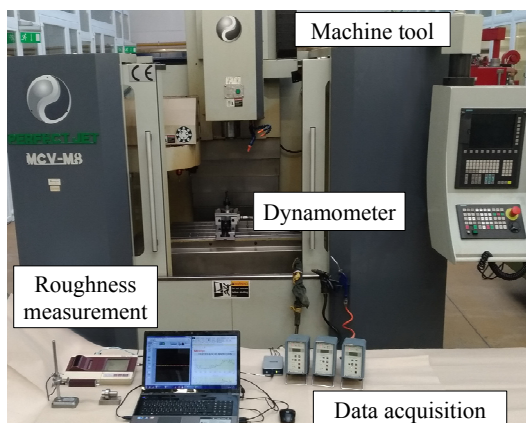


Figure 2. Experimental setup

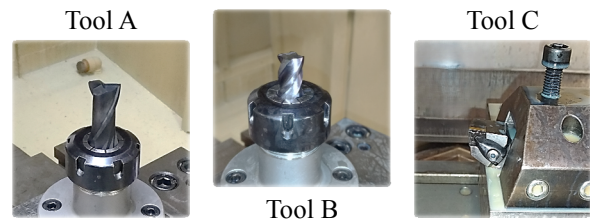


Figure 3. Cutting tools used in the experiment

To reduce friction and heat generation during the machining process, a 5% emulsion of Rhenus TS 25 coolant and lubricant was applied through external spraying, providing both cooling and lubrication in the cutting zone. The workpieces were normalized C45 medium-carbon steel shafts, chosen for their industrial relevance and good machinability. Each specimen had a cylindrical surface to be machined with a diameter of 40 mm, a length of 12 mm, and a Vickers hardness of 220 HV. The normalization heat treatment ensured uniform microstructure and mechanical properties across the workpieces. Three different tool configurations were tested, including two rotational turning tools and one conventional longitudinal turning tool. These are illustrated in Figure 2:

- Tool A (Rotational, 30° inclination): Fraisa P5300682 end mill (HM MG10), with a 30° inclination angle and 20 mm diameter.
- Tool B (Rotational, 45° inclination): Sandvik Coromant 1P341-1600-XB end mill, where 3 of 4 cutting edges were ground down, ensuring only a single active cutting edge during operation. The inclination angle was 45°, with a diameter of 16 mm and tool material of grade 1630.
- Tool C (Conventional longitudinal turning tool): Sandvik Coromant insert CNMG 120412-PM, mounted in a DCLNL 2525 M 12 holder, with a tool grade of 4325.

The cutting tests were designed to provide variation in three primary cutting parameters to study the energy efficiency in a wide range of setups. Based on the machined material and the cutting tools, different values for the setup parameters were chosen for the experiments according to the recommendations of tool manufacturers, industrial practices and previous experiences: depth of cut ( $a_p$ ): 0.1 mm, 0.2 mm, 0.3 mm; feed ( $f$ ): 0.2 mm/rev, 0.6 mm/rev, 1.0 mm/rev; cutting speed ( $v_c$ ): 200 m/min, 250 m/min. The selected combination of these resulted in a comprehensive matrix of setups, ensuring that the influence of each parameter and tool geometry could be evaluated. Table 1 summarizes all combinations of parameters used in the experimental program.

Each experimental setup is uniquely identified using a two-part designation: a letter indicating the tool used and a number corresponding to the cutting parameter combination. The setup number (1–12) refers to a specific combination of depth of cut, feed, and cutting speed, as summarized in Table 1. For example, Setup A3 refers to the experiment performed with Tool A under the cutting conditions defined as Setup 3 ( $a_p = 0.1$  mm,  $f = 1.0$  mm/rev,  $v_c = 200$  m/min), while Setup C12 indicates an experiment performed with Tool C under the conditions of Setup 12 ( $a_p = 0.3$  mm,  $f = 1.0$  mm/rev,

$v_c = 200$  m/min). All tests were carried out using standardized clamping configurations optimized for each turning procedure, ensuring process stability and proper alignment. Although the fixturing systems for the rotational and longitudinal turning tools differed due to their geometric and functional requirements, each setup was designed to provide repeatable and rigid tool holding, minimizing external variability and ensuring the reliability of force and surface measurements.

**Table 1. Experimental setup**

| Setup number | $a_p$<br>[mm] | $f$<br>[mm/rev] | $v_c$<br>[m/min] |
|--------------|---------------|-----------------|------------------|
| 1            | 0.1           | 0.2             | 200              |
| 2            | 0.1           | 0.6             | 200              |
| 3            | 0.1           | 1               | 200              |
| 4            | 0.1           | 0.2             | 250              |
| 5            | 0.1           | 0.6             | 250              |
| 6            | 0.1           | 1               | 250              |
| 7            | 0.2           | 0.2             | 200              |
| 8            | 0.2           | 0.6             | 200              |
| 9            | 0.2           | 1               | 200              |
| 10           | 0.3           | 0.2             | 200              |
| 11           | 0.3           | 0.6             | 200              |
| 12           | 0.3           | 1               | 200              |

## 2.2 Measurement Methods

The cutting forces were recorded in real-time using a Kistler 9257A three-component piezoelectric dynamometer, which was mounted between the machine table and the tool fixture. The dynamometer measured the force components  $F_x$ ,  $F_y$  and  $F_z$  in the machine coordinate system. These signals were transmitted through three Kistler 5011 single-channel charge amplifiers, converted to voltage signals, and digitized using a National Instruments NI-9215 Analog Input Module housed in a cDAQ-9171 chassis. Data acquisition was performed using NI LabVIEW software, with a sampling frequency of 1000 Hz, ensuring high temporal resolution of the cutting process. The raw force data were continuously recorded during each machining pass. Since the dynamometer measures forces in the machine coordinate system, a transformation was required to convert these into the tool coordinate system. Using the known and continuously changing relative position of the tool and the workpiece, the following force components were calculated for each time point in the function of the elapsed time ( $t$ ):

- $F_c(t)$  – Main cutting force (tangential component)
- $F_f(t)$  – Feed force (axial component)
- $F_p(t)$  – Passive or thrust force (radial component)

Surface roughness characterization was conducted using the following procedure. Profile measurements were carried out with a Mitutoyo Surf Test SJ-301 portable surface roughness tester. Measurements were taken on three generatrix lines evenly spaced around the turned surface of each sample. The registered profiles were processed and analysed using Alti Map Premium 6.2.7487 software, in accordance with ISO 21920: 2021. The cut-off length was selected based on feed rate: 0.8 mm for 0.2 mm/rev feed rate; 2.5 mm for the 0.6 and 1.0

mm/rev feed rates. The focus of the roughness analysis was on  $R_a$  (arithmetical mean roughness) and  $R_z$  (maximum peak-to-valley height), calculated as the mean of the three 2D measurements per setup. These values were analysed as functions of feed rate and tool geometry, allowing for comparison between rotational and longitudinal turning processes. The measurement procedures ensured compliance with metrological standards, while the dual-device approach enabled a deeper understanding of the profile characteristics.

## 3. RESULTS

This section presents the measured and calculated results from the turning experiments conducted with the three different tool configurations (Tools A, B, and C) under twelve machining setups each. The complete dataset is summarized in Table 2, which includes all 36 unique setups (A1–A12, B1–B12, C1–C12) and the corresponding measured and calculated results.

The investigated output parameters include the maximum cutting forces in the tool coordinate system (tangential force  $F_c$ , feed force  $F_f$ , and passive force  $F_p$ ), the corresponding specific cutting forces, the total mechanical work performed during cutting ( $W_t$ ), and the surface roughness parameters: arithmetical mean roughness ( $R_a$ ) and maximum peak-to-valley height ( $R_z$ ).

The maximum values of the  $F_c(t)$ ,  $F_f(t)$ , and  $F_p(t)$  curves during the constant cross-section phase of cutting were determined for each setup and used as representative values. From these, the specific cutting forces in each direction ( $k_c$ ,  $k_f$ ,  $k_p$ ) were calculated by dividing the measured cutting force by the cross-sectional area of the uncut chip:

$$k_i = \frac{F_i}{a_p \cdot f} \quad (i = c, f, p) \quad (1)$$

This allowed for comparison of tool loading under varying conditions, normalized by material removal volume.

The mechanical work done ( $W_t$ ) during cutting was calculated by evaluating the contribution of force and motion in both the tangential (cutting) and axial (feed) directions. Since no primary movement occurs in the radial direction, the corresponding force component was neglected in the work calculation. Mathematically, the work in each direction was computed as:

$$W_i = \int_0^{t_0} F_i(t) \cdot v_i dt \quad (i = c, f) \quad (2)$$

where  $F_i(t)$  is the time-dependent force component and  $v_i$  is the corresponding velocity component in direction  $i$  (either  $c$  = tangential or  $f$  = axial).

For each experimental setup, the total work was obtained as the sum of the work in the tangential and axial directions, calculated by integrating the product of the force and velocity components with respect to time during the constant cross-section phase of the cut. The total mechanical work was then:

$$W_t = W_c + W_f \quad (3)$$

**Table 2. Experimental results of the maximum cutting force components, the corresponding specific cutting forces, the total mechanical work performed during cutting, and the surface roughness parameters**

| Setup | $F_c$ | $F_f$ | $F_p$ | $k_c$                                         | $k_f$                                         | $k_p$                                         | $W_t$ | $R_{a1}$          | $R_{a2}$          | $R_{a3}$          | $R_a$             | $R_{z1}$          | $R_{z2}$          | $R_{z3}$          | $R_z$             |
|-------|-------|-------|-------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|-------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
|       | [N]   | [N]   | [N]   | $\left[ \frac{\text{N}}{\text{mm}^2} \right]$ | $\left[ \frac{\text{N}}{\text{mm}^2} \right]$ | $\left[ \frac{\text{N}}{\text{mm}^2} \right]$ | [J]   | [ $\mu\text{m}$ ] | [ $\mu\text{m}$ ] | [ $\mu\text{m}$ ] | [ $\mu\text{m}$ ] | [ $\mu\text{m}$ ] | [ $\mu\text{m}$ ] | [ $\mu\text{m}$ ] | [ $\mu\text{m}$ ] |
| A01   | 79.6  | 20.2  | 48.3  | 3979                                          | 1012                                          | 2413                                          | 621   | 0.47              | 0.48              | 0.49              | 0.48              | 3.82              | 3.79              | 3.73              | 3.78              |
| A02   | 178.3 | 51.2  | 90.6  | 2972                                          | 854                                           | 1510                                          | 468   | 0.73              | 0.69              | 0.74              | 0.72              | 5.18              | 5.19              | 5.67              | 5.35              |
| A03   | 268.9 | 80.4  | 126.9 | 2689                                          | 804                                           | 1269                                          | 419   | 1.15              | 1.08              | 1.14              | 1.12              | 7.39              | 6.57              | 7.35              | 7.10              |
| A04   | 77.7  | 20.6  | 46.8  | 3885                                          | 1032                                          | 2339                                          | 605   | 0.45              | 0.45              | 0.44              | 0.45              | 3.81              | 3.80              | 3.78              | 3.80              |
| A05   | 176.1 | 52.1  | 89.3  | 2935                                          | 869                                           | 1488                                          | 462   | 0.76              | 0.74              | 0.78              | 0.76              | 5.95              | 5.19              | 5.39              | 5.51              |
| A06   | 265.0 | 81.6  | 120.1 | 2650                                          | 816                                           | 1201                                          | 420   | 1.63              | 1.62              | 1.57              | 1.61              | 9.44              | 8.94              | 9.90              | 9.43              |
| A07   | 149.1 | 41.3  | 79.8  | 3728                                          | 1032                                          | 1995                                          | 1162  | 0.53              | 0.53              | 0.53              | 0.53              | 4.42              | 4.36              | 4.30              | 4.36              |
| A08   | 333.9 | 102.7 | 155.0 | 2783                                          | 856                                           | 1292                                          | 870   | 0.81              | 0.75              | 0.78              | 0.78              | 5.78              | 5.62              | 5.59              | 5.66              |
| A09   | 501.4 | 159.3 | 235.3 | 2507                                          | 797                                           | 1176                                          | 795   | 1.93              | 1.81              | 1.91              | 1.88              | 10.03             | 9.30              | 9.20              | 9.51              |
| A10   | 222.7 | 65.3  | 103.7 | 3712                                          | 1089                                          | 1729                                          | 1724  | 0.47              | 0.51              | 0.49              | 0.49              | 3.76              | 3.67              | 3.55              | 3.66              |
| A11   | 548.3 | 174.2 | 248.1 | 3046                                          | 968                                           | 1378                                          | 1400  | 0.85              | 0.81              | 0.92              | 0.86              | 5.24              | 5.28              | 5.89              | 5.47              |
| A12   | 840.0 | 279.1 | 341.0 | 2800                                          | 930                                           | 1137                                          | 1287  | 1.98              | 2.17              | 1.76              | 1.97              | 9.42              | 9.46              | 8.55              | 9.14              |
| B01   | 81.1  | 28.7  | 38.0  | 4057                                          | 1434                                          | 1898                                          | 624   | 0.78              | 0.71              | 0.71              | 0.73              | 5.24              | 5.23              | 4.73              | 5.07              |
| B02   | 186.2 | 72.6  | 69.2  | 3103                                          | 1211                                          | 1153                                          | 466   | 2.03              | 1.97              | 1.92              | 1.97              | 10.93             | 10.35             | 10.19             | 10.49             |
| B03   | 273.5 | 111.1 | 88.2  | 2735                                          | 1111                                          | 882                                           | 412   | 4.96              | 4.93              | 4.97              | 4.95              | 22.44             | 22.43             | 22.20             | 22.36             |
| B04   | 81.7  | 30.2  | 39.4  | 4087                                          | 1511                                          | 1970                                          | 622   | 0.46              | 0.78              | 0.69              | 0.64              | 5.47              | 5.28              | 5.06              | 5.27              |
| B05   | 181.4 | 74.8  | 66.2  | 3023                                          | 1247                                          | 1104                                          | 458   | 2.25              | 2.12              | 2.08              | 2.15              | 11.31             | 10.70             | 10.16             | 10.72             |
| B06   | 265.4 | 113.7 | 79.3  | 2654                                          | 1137                                          | 793                                           | 403   | 5.13              | 4.85              | 5.08              | 5.02              | 23.71             | 21.97             | 21.91             | 22.53             |
| B07   | 163.1 | 63.7  | 74.1  | 4076                                          | 1593                                          | 1853                                          | 1206  | 0.74              | 0.74              | 0.71              | 0.73              | 5.24              | 5.15              | 5.05              | 5.15              |
| B08   | 362.2 | 160.9 | 112.1 | 3019                                          | 1341                                          | 934                                           | 876   | 2.02              | 2.05              | 1.92              | 2.00              | 11.21             | 10.03             | 9.62              | 10.29             |
| B09   | 528.3 | 247.3 | 125.2 | 2641                                          | 1237                                          | 626                                           | 774   | 5.48              | 5.70              | 5.51              | 5.56              | 23.95             | 23.14             | 22.46             | 23.18             |
| B10   | 246.1 | 106.1 | 98.7  | 4102                                          | 1768                                          | 1645                                          | 1804  | 0.68              | 0.72              | 0.72              | 0.71              | 4.90              | 4.83              | 4.51              | 4.75              |
| B11   | 536.4 | 263.1 | 125.6 | 2980                                          | 1462                                          | 698                                           | 1309  | 2.14              | 2.04              | 2.04              | 2.07              | 11.07             | 10.88             | 9.52              | 10.49             |
| B12   | 804.8 | 407.1 | 146.1 | 2683                                          | 1357                                          | 487                                           | 1173  | 4.36              | 4.75              | 4.13              | 4.41              | 21.15             | 20.77             | 18.97             | 20.30             |
| C01   | 80.8  | 16.9  | 89.3  | 4038                                          | 847                                           | 4463                                          | 647   | 0.96              | 0.99              | 0.94              | 0.96              | 4.44              | 5.00              | 4.46              | 4.63              |
| C02   | 176.4 | 20.5  | 161.6 | 2940                                          | 342                                           | 2694                                          | 466   | 6.68              | 6.49              | 6.57              | 6.58              | 25.74             | 25.54             | 25.67             | 25.65             |
| C03   | 272.8 | 23.9  | 239.9 | 2728                                          | 239                                           | 2399                                          | 432   | 12.83             | 13.51             | 13.09             | 13.14             | 50.70             | 50.86             | 50.63             | 50.73             |
| C04   | 78.7  | 18.0  | 94.4  | 3933                                          | 900                                           | 4722                                          | 630   | 0.99              | 0.92              | 1.02              | 0.98              | 4.77              | 4.42              | 4.84              | 4.68              |
| C05   | 174.4 | 19.9  | 164.6 | 2906                                          | 332                                           | 2743                                          | 466   | 6.69              | 6.65              | 6.86              | 6.73              | 26.08             | 26.16             | 26.55             | 26.26             |
| C06   | 286.6 | 28.6  | 253.0 | 2866                                          | 286                                           | 2530                                          | 453   | 13.29             | 13.56             | 13.35             | 13.40             | 51.81             | 52.27             | 51.47             | 51.85             |
| C07   | 137.2 | 38.4  | 144.2 | 3429                                          | 961                                           | 3604                                          | 1099  | 0.92              | 0.91              | 0.93              | 0.92              | 4.58              | 4.44              | 4.50              | 4.51              |
| C08   | 302.7 | 46.9  | 232.2 | 2523                                          | 391                                           | 1935                                          | 815   | 7.14              | 7.13              | 7.12              | 7.13              | 27.21             | 27.38             | 27.24             | 27.28             |
| C09   | 459.3 | 52.5  | 319.3 | 2297                                          | 262                                           | 1596                                          | 727   | 13.88             | 14.12             | 13.44             | 13.81             | 53.14             | 52.53             | 51.67             | 52.45             |
| C10   | 188.6 | 61.1  | 171.4 | 3143                                          | 1019                                          | 2857                                          | 1513  | 0.94              | 0.91              | 0.92              | 0.92              | 4.56              | 4.40              | 4.59              | 4.52              |
| C11   | 425.7 | 79.4  | 287.7 | 2365                                          | 441                                           | 1598                                          | 1133  | 7.02              | 6.90              | 6.94              | 6.95              | 26.83             | 26.93             | 26.77             | 26.84             |
| C12   | 649.1 | 82.4  | 395.8 | 2164                                          | 275                                           | 1319                                          | 1043  | 13.57             | 13.79             | 13.52             | 13.63             | 54.22             | 52.68             | 52.50             | 53.13             |

#### 4. DISCUSSION

This section provides a detailed analysis of the experimental results obtained from the comparative study of rotational and longitudinal turning. The discussion focuses on five main aspects: the evolution of the cutting force components, the behaviour of specific cutting forces, the total mechanical work input during machining, the resulting surface roughness characteristics, and the relation between the finished surface roughness and the work done. Each of these parameters is evaluated as a function of the setup parameters and compared across the three tool types.

##### 4.1 Cutting Force Components

The cutting forces acting during turning provide essential understanding into the mechanical load acting on the

tool and workpiece. In this study, the tangential ( $F_c$ ), feed ( $F_f$ ), and passive ( $F_p$ ) force components were measured for all three tool types (A, B, C) under twelve identical machining parameter sets. Figure 4–6 show the alteration of the maximum values of the three main force components.

An increase in the depth of cut from 0.1 mm to 0.3 mm generally resulted in substantial growth in all force components for all tool types. For example, in rotational turning with Tool A at constant feed ( $f = 0.2$  mm/rev,  $v_c = 200$  m/min),  $F_c$  rose from 79.6 N (Setup A01) to 222.7 N (A10) – an increase of approximately 179.8%. Similarly,  $F_f$  grew from 20.2 N to 65.3 N (+223.2%), and  $F_p$  from 48.3 N to 103.7 N (+114.7%). This trend is consistent for Tools B and C as well. With Tool C, under the same cutting conditions (Setups C01, C07, C10),  $F_c$  increased from 80.8 N to 188.6 N (+133.4%), showing that longitudinal turning also exhibits strong

dependence on  $a_p$ , although Tool A generated lower forces for the same  $a_p$  increment. This suggests more efficient chip engagement and reduced load per unit depth in rotational turning – likely due to the inclined cutting edge modifying the effective rake and chip thickness.

The feed rate significantly influenced all three force components. With Tool A, increasing feed from 0.2 to 1.0 mm/rev (Setups A01 to A03,  $a_p = 0.1$  mm,  $v_c = 200$  m/min) caused  $F_c$  to grow from 79.6 N to 268.9 N, marking a 237.7% increase.  $F_f$  grew even more sharply: from 20.2 N to 80.4 N (+298.0%), indicating a strong correlation between feed and axial loading.  $F_p$  rose from 48.3 N to 126.9 N (+162.7%). Similar behaviour is observed for Tools B and C. For example, Tool C at  $a_p = 0.1$  mm,  $v_c = 200$  m/min (Setups C01 → C03) showed  $F_c$  increasing from 80.8 N to 272.8 N (+237.5%), and  $F_p$  from 89.3 N to 239.9 N (+168.6%). The steeper rise in  $F_f$  with Tool B (from 28.7 N to 111.1 N, +287.4%) displays the additional axial engagement due to the inclined cutting edge, especially at higher feeds. In general, higher feeds increase uncut chip thickness, which proportionally affects both  $F_c$  and  $F_f$ . However, the rate of increase is also influenced by tool geometry. The rotational tools (A and B) show slightly more moderate force growth than Tool C, especially in the feed direction, suggesting that rotational turning may reduce axial tool loading at high feeds – a potential advantage in high-feed machining.

The influence of cutting speed (from 200 m/min to 250 m/min) on cutting forces was more moderate than that of  $a_p$  and  $f$ . For example, Tool A at  $f = 0.2$  mm/rev and  $a_p = 0.1$  mm showed a slight decrease in  $F_c$  from 79.6 N to 77.7 N (−2.4%) and in  $F_p$  from 48.3 N to 46.8 N (−3.1%). This mild reduction is potentially attributed to thermal softening of the workpiece material at higher speeds and possibly improved chip flow. However, the effect is not universally consistent across all conditions. With Tool B, at  $f = 0.2$  mm/rev and  $a_p = 0.1$  mm (B01 → B04),  $F_c$  remained nearly unchanged (81.1 N to 81.7 N), while  $F_f$  increased from 28.7 N to 30.2 N (+5.2%). With Tool C,  $F_c$  decreased slightly (C01 → C04: 80.8 N → 78.7 N, −2.6%) and  $F_p$  increased (89.3 N → 94.4 N, +5.7%). This variation indicates that while speed can influence force levels, it interacts more subtly with cutting edge engagement and tool wear than feed or depth of cut. When comparing tool types directly under identical conditions, significant differences appear. For example, at Setup 03,  $F_c$  values were Tool A: 268.9 N, Tool B: 273.5 N, Tool C: 272.8 N. These results indicate similar tangential force levels across all tools at high feed and low depth, suggesting that chip load per edge dominates in this range. In contrast, the feed force varied more significantly: Tool A: 80.4 N, Tool B: 111.1 N, Tool C: 23.9 N. Tool C showed much lower axial force, which is expected, as axial force in longitudinal turning acts parallel to the feed, while in rotational turning (especially with inclined tools), axial load includes components redirected by the tool inclination. However, the  $F_f$  of Tool B was 38.1% higher than of Tool A, showing that the 45° inclination induces greater axial load than the 30° tool at high feed. The radial force also showed tool-dependent differences. For

instance, at Setup 09,  $F_p$  values were Tool A: 235.3 N, Tool B: 125.2 N, Tool C: 319.3 N.

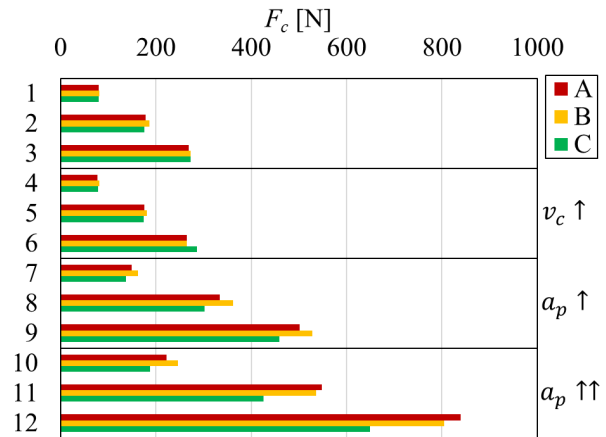


Figure 4. Maximum tangential cutting force ( $F_c$ ) for all setups using Tools A, B, and C

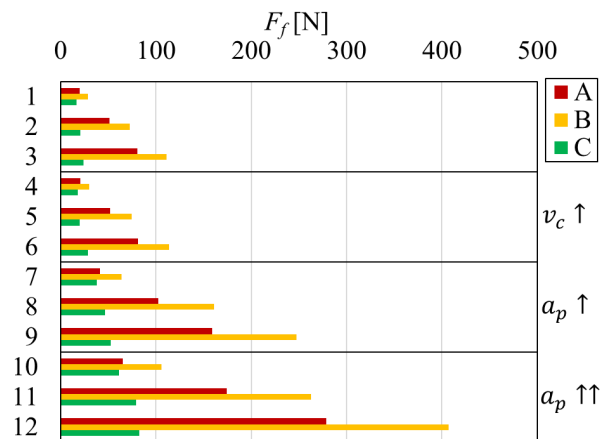


Figure 5. Maximum feed directional force ( $F_f$ ) recorded in the experiments for each tool and setup combination

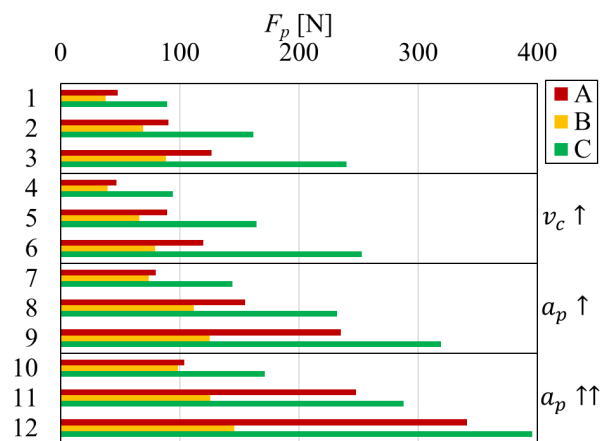


Figure 6. Maximum passive force ( $F_p$ ) measured during the cutting tests across all tool configurations and parameters

Here, Tool C produced the highest radial force, while Tool B yielded the lowest. This may be attributed to the inclined cutting action in Tools A and B, which distributes force more toward the feed and tangential directions and reduces direct thrust into the workpiece.

Overall, the comparison of the cutting force components suggests that rotational turning tools – especially the 30° version, Tool A – can reduce radial and axial loads, especially at high feeds and low-to-medium dep–

ths. While tangential force trends are similar across all tools, the distribution of force components differs significantly, and this can influence tool deflection, part accuracy, and surface integrity in downstream analysis.

## 4.2 Specific Cutting Forces

The specific main cutting force, specific feed force, and specific passive force offer normalized measures of cutting load by expressing the force required per unit of uncut chip cross-section. Figures 7–9 present the specific values of the cutting force components, calculated as shown in Equation 1.

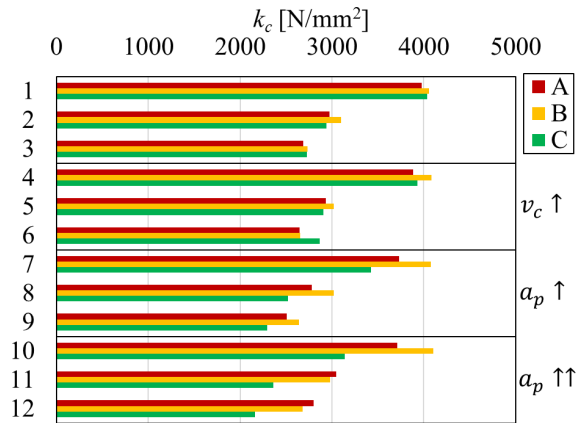


Figure 7. Specific cutting force in the tangential direction ( $k_c$ ) calculated for each experimental setup

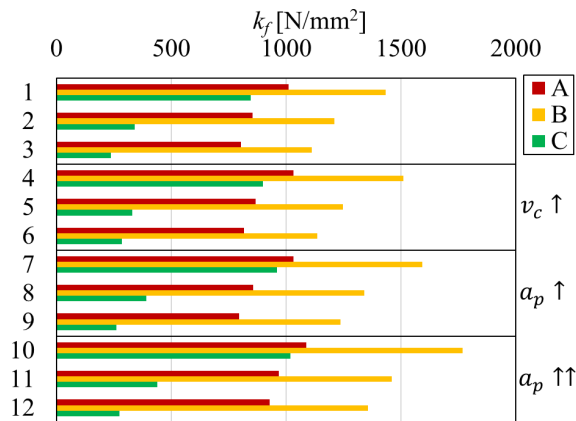


Figure 8. Specific feed directional cutting force ( $k_f$ ) determined for the three tool types and cutting conditions

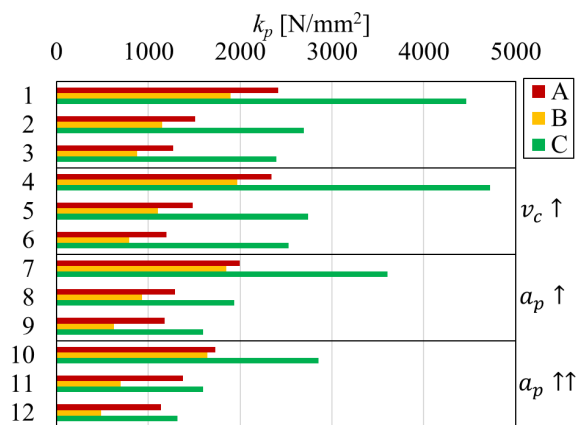


Figure 9. Specific passive cutting force ( $k_p$ ) obtained for all machining setups.

These parameters enable better comparison across different feed rates and depths of cut, eliminating size effects. This section discusses how these specific force values are influenced by the cutting parameters and tool geometry and highlights the differences between rotational turning tools (A and B) and the conventional longitudinal turning tool (C).

Feed rate had a strong influence on the specific cutting forces, particularly  $k_c$ . With increasing feed,  $k_c$  showed a clear decreasing trend, which is consistent with classical machining theory: as uncut chip thickness increases, the force per unit area tends to decrease due to improved shearing efficiency and the reduced influence of the edge radius. For instance, with Tool A at  $a_p = 0.1$  mm and  $v_c = 200$  m/min (Setups A01 to A03),  $k_c$  decreased from 3979.3 N/mm<sup>2</sup> ( $f = 0.2$  mm/rev) to 2689.2 N/mm<sup>2</sup> ( $f = 1.0$  mm/rev), a 32.4% reduction;  $k_f$  dropped from 1011.7 to 803.7 N/mm<sup>2</sup> (−20.6%);  $k_p$  declined from 2413.1 to 1269.3 N/mm<sup>2</sup> (−47.4%). Similar reductions were observed with Tool B:  $k_c$  dropped from 4057.3 to 2735.2 N/mm<sup>2</sup> (−32.6%),  $k_f$  fell from 1434.4 to 1111.3 N/mm<sup>2</sup> (−22.5%);  $k_p$  decreased from 1898.5 to 882.1 N/mm<sup>2</sup> (−53.5%). Tool C followed the same pattern but started from slightly higher  $k_c$  at low feed and declined to even lower levels at high feed ( $k_c$  fell from 4038.1 to 2728.3 N/mm<sup>2</sup>, −32.5%). This inverse relationship highlights the economic potential of increasing feed rate, especially when tool deflection and surface integrity errors are acceptable. Interestingly,  $k_p$  dropped much more sharply with increasing feed than  $k_c$ , indicating that radial force is more sensitive to chip thickness. This could be due to better chip curling and evacuation at higher feeds, reducing resistance perpendicular to the cutting direction.

Contrary to the feed rate, increasing depth of cut generally resulted in stable or slightly increasing specific cutting forces, depending on the tool. For example, with Tool A at constant feed ( $f = 0.2$  mm),  $k_c$  changed only slightly: A01 ( $a_p = 0.1$ ): 3979.3 N/mm<sup>2</sup>, A07 ( $a_p = 0.2$  mm): 3728.4 N/mm<sup>2</sup> (−6.3%), A10 ( $a_p = 0.3$  mm): 3711.9 N/mm<sup>2</sup> (−0.4%). This indicates that  $k_c$  becomes more consistent at higher  $a_p$ , showing that cutting is more volume-dominant and less affected by edge effects. Tool B and Tool C showed similar trends. In Tool C at  $f = 0.2$  mm/rev,  $k_c$  decreased from 4038.1 N/mm<sup>2</sup> ( $a_p = 0.1$  mm) to 3143.0 N/mm<sup>2</sup> ( $a_p = 0.3$  mm), a 22.2% decrease. Interestingly, despite Tool C being a traditional longitudinal tool, it showed a more pronounced reduction in  $k_c$  with increasing  $a_p$ . This may be due to less effective chip engagement at lower  $a_p$  in longitudinal turning, where tool nose radius and clearance become more critical.

The cutting speed (from 200 to 250 m/min) had a relatively minor effect on  $k_c$ ,  $k_f$ , and  $k_p$  across all tool types. For example, with Tool A at  $a_p = 0.1$  mm,  $f = 0.2$  mm  $k_c$  decreased slightly from 3979.3 (A01) to 3884.8 N/mm<sup>2</sup> (A04), a −2.4% reduction. Similar small reductions were observed in Tool B (−1.7%) and Tool C (−2.6%). These reductions are likely due to thermal softening of the workpiece material and reduced friction at higher cutting speeds. However, the influence remains moderate in the investigated range. Comparing

specific forces under identical conditions reveals important tool-dependent differences. For example, at Setup 03 ( $a_p = 0.1$  mm,  $f = 1.0$  mm/rev,  $v_c = 200$  m/min),  $k_c$  values were: Tool A: 2689.2 N/mm<sup>2</sup>, Tool B: 2735.2 N/mm<sup>2</sup>, Tool C: 2728.3 N/mm<sup>2</sup>. The  $k_c$  values are nearly identical here, suggesting that at high feed and low depth, all three tools engage similar chip section areas. However, the differences in  $k_f$  are more revealing: Tool A: 803.7 N/mm<sup>2</sup>, Tool B: 1111.3 N/mm<sup>2</sup>, Tool C: 238.6 N/mm<sup>2</sup>. The significantly lower  $k_f$  of Tool C (by about 70%) at the same setup indicates that axial loading is substantially reduced in longitudinal turning, as expected. Conversely, rotational tools induce more axial stress due to the inclination of the cutting edge. Radial specific forces also varied considerably: Tool A: 1269.3 N/mm<sup>2</sup>, Tool B: 882.1 N/mm<sup>2</sup>, Tool C: 2398.7 N/mm<sup>2</sup>. Here, Tool C exhibited the highest radial specific load, over 89% higher than Tool A, and nearly 172% higher than Tool B. This suggests that rotational turning reduces radial force per unit area – a major advantage in minimizing tool deflection and improving dimensional accuracy. Looking at larger cuts (Setup 12:  $a_p = 0.3$  mm,  $f = 1.0$  mm,  $v_c = 200$  m/min), the  $k_c$  values were 2799.9 N/mm<sup>2</sup> in A12, 2682.6 N/mm<sup>2</sup> in B12, and 2163.6 N/mm<sup>2</sup> in C12. Here, Tool C shows the lowest  $k_c$ , likely due to improved material shearing at greater chip loads. However, its  $k_p$  remains the highest (1319.3 N/mm<sup>2</sup> compared to 1136.8 N/mm<sup>2</sup> for A12 and 487.0 N/mm<sup>2</sup> for B12), confirming that radial loading remains a concern in longitudinal turning.

The analysis of the specific forces revealed interesting alterations. Increasing feed consistently reduces  $k_c$ ,  $k_f$ , and  $k_p$  across all tools. Increasing  $a_p$  results in more stable  $k_c$  values, with minor reductions or plateaus. Cutting speed causes slight reductions in specific forces, attributed to thermal effects. Rotational tools reduce  $k_p$ , especially Tool B, which shows the lowest radial specific load. Longitudinal turning (Tool C) shows lowest axial specific forces but highest radial ones, indicating a trade-off between stability and part deflection. These findings confirm that rotational turning – especially with higher inclination – can redistribute the cutting load, potentially lowering radial deflection values and enabling higher feeds while maintaining manageable tool stresses.

### 4.3 Total Work Done

The total mechanical work done during the cutting process is a fundamental metric of energy demand in machining. In our study, it reflects the combined force and displacement contributions in the tangential and feed directions over the duration of material removal. In this study, the total work was determined by integrating the product of force and velocity over time in the cutting and feed directions, neglecting the radial direction due to the lack of relative motion in that axis. This section explores the effects of cutting parameters and tool geometry on the energy requirement per cut and compares the three tool types to assess the implications for energy-efficient machining. Figure 10 shows the results of the calculations based on Equations 2–3.

The feed rate had a definite and consistent effect on  $W_t$  across all tools and depths of cut. For instance, at  $a_p = 0.1$  mm and  $v_c = 200$  m/min, Tool A showed the following  $W_t$  values: 620.8 J in A01, 468.2 J in A02, 419.4 J in A03. Although the material removal rate increased significantly, the total work decreased with higher feed. Between A01 and A03,  $W_t$  dropped by 32.5%, even though the feed was multiplied by a factor of five. This counterintuitive result highlights the efficiency gains of high-feed machining: although direct cutting forces increase, the shorter cutting time and lower specific forces result in reduced total energy input. Similar trends were observed with Tools B and C. For example, with Tool C under the same conditions the following results were calculated: 646.5 J in C01, 466.3 J in C02 (–27.9%), 431.9 J in C03 (–33.2%). This consistent decrease in  $W_t$  with increasing feed further supports the recommendation for using higher feeds – within surface quality and machine rigidity constraints – as a strategy for reducing energy consumption.

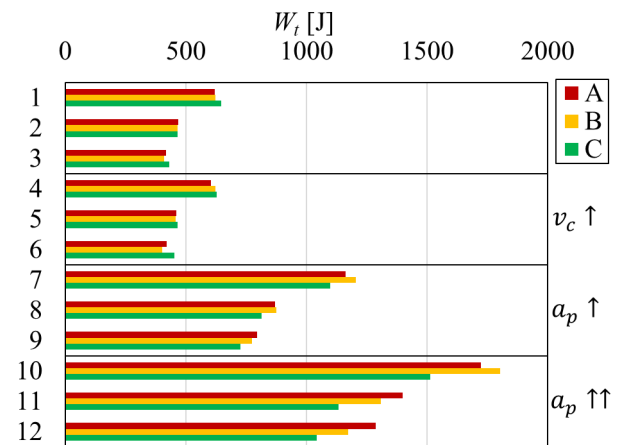


Figure 10. Total mechanical work done ( $W_t$ ) during the cutting process for each setup and tool configuration.

Contrary to the feed effect, increasing the depth of cut significantly increased the total work done, due to the larger volume of material removed and higher resistance encountered. For instance, with Tool A at  $f = 0.2$  mm and  $v_c = 200$  m/min the following work values were calculated: 620.8 J in A01, 1162.3 J in A07, 1723.7 J in A10. From A01 to A10,  $W_t$  increased by 177.6%, closely proportional to the growth in cross-sectional area of the cut. Similar proportional increases were observed with the other tools. For example, the following were determined for Tool C: 646.5 J in C01, 1099.4 J in C07 (+70.1%), 1512.8 J in C10 (+134%). Although Tool C also showed rising work with  $a_p$ , the relative increase was less steep than for Tool A, likely due to higher  $k_c$  of Tool C at low  $a_p$ , which becomes less dominant as  $a_p$  increases and cutting stabilizes.

The cutting speed had a minimal impact on total work done. For instance, with Tool A at  $a_p = 0.1$  mm and  $f = 0.2$  mm/rev  $W_t$  was 620.8 J in A01 and 605.0 J in A04 (–2.5%). This minor reduction may be attributed to decreased cutting forces at higher speed due to thermal softening. However, the effect is generally negligible compared to feed and depth of cut. Similar small reductions were seen across Tools B and C (for example, C01 → C04 shows a –2.6% difference in the results).

At identical cutting conditions, significant differences in  $W_t$  were observed among the three tools. For Setup 03, the total work was: 419.4 J in A03, 411.6 J in B03, 431.9 J in C03. Here, Tools A and B (rotational) required slightly less work (−2.9% and −4.7%) than Tool C. This confirms that, despite higher direct force magnitudes, the overall energy requirement is slightly reduced in rotational turning under high-feed, low-ap conditions. More pronounced differences emerged at deeper cuts. At Setup 12, the following work values were calculated: 1286.6 J in A12, 1173.4 J in B12, 1043.5 J in C12. Tool C showed the lowest  $W_t$ , likely due to more favourable chip flow and material shearing at high volumes in longitudinal turning. However, this comes at the cost of higher radial and axial loading, as shown in earlier sections. Interestingly, Tool B consistently showed the lowest energy requirement in many conditions despite its 45° inclination, which tends to increase axial loading. This suggests that its geometry may offer a favourable rake angle and chip flow that minimizes resistance during chip formation. Across all 36 setups, the mean total work values were: 926.2 J for Tool A, 889.2 J for Tool B, and 902.6 J for Tool C. While these values are relatively close, Tool B shows a slight overall advantage (~4% lower  $W_t$ ). This difference, though moderate, may translate into significant savings in large-scale or continuous machining environments, supporting the industrial relevance of rotational turning.

The calculation of the work done led to the following observations. Increasing feed noticeably reduces  $W_t$ , due to shortened engagement time and decreased  $k_c$ . Increasing depth of cut leads to proportional increases in energy input. Cutting speed has a minor effect on total work. Rotational tools (A and B) require less energy than longitudinal Tool C at high feed–low ap conditions. Tool B (45°) showed the lowest average energy requirement, suggesting that its edge inclination may be optimal for chip engagement and cutting efficiency. These findings confirm that rotational turning is not only viable but can be more energy efficient than conventional turning under appropriate cutting conditions, especially when configured with well-designed tool geometries.

#### 4.4 Surface Roughness

Surface roughness is a key indicator of the quality and functional performance of a machined part, influencing wear, friction and fatigue behaviour. In this study, both  $R_a$  (arithmetical mean roughness) and  $R_z$  (peak-to-valley height) were measured to characterize the surface topography of the turned parts. Their average values are presented in Figure 11 ( $R_a$ ) and in Figure 12 ( $R_z$ ).

Feed rate showed the strongest influence on surface roughness. Across all tools, increasing the feed from 0.2 mm/rev to 1.0 mm/rev led to significant increases in both  $R_a$  and  $R_z$ . This trend aligns with theoretical expectations: higher feed rates increase the spacing and depth of tool marks on the surface, resulting in rougher textures. For example, using Tool A at  $a_p = 0.1$  mm and  $v_c = 200$  m/min resulted in the following:  $R_a$  increased from 0.48  $\mu\text{m}$  (A01) to 1.123  $\mu\text{m}$  (A03), which is a +134% increase;  $R_z$  rose from 3.78  $\mu\text{m}$  to 7.103  $\mu\text{m}$ , a

+87.9% increase. Tool B showed even more intense changes:  $R_a$  went from 0.733  $\mu\text{m}$  (B01) to 4.953  $\mu\text{m}$  (B03) (+575%), while  $R_z$  rose from 5.066  $\mu\text{m}$  to 22.356  $\mu\text{m}$  (+341%). Tool C (longitudinal) also exhibited steep increases:  $R_a$ : 0.963  $\mu\text{m} \rightarrow 13.143 \mu\text{m}$  (+1265%),  $R_z$ : 4.633  $\mu\text{m} \rightarrow 50.73 \mu\text{m}$  (+995%). These results clearly demonstrate that longitudinal turning is much more sensitive to feed increase in terms of surface roughness. The use of a single-point insert in Tool C produces a regular feed mark profile, which becomes deeper and wider at higher feed rates. In contrast, rotational tools A and B, which cut with an inclined edge and produce overlapping tool paths, generate more compressed surface features even at high feed.

Depth of cut had a much weaker influence on surface roughness compared to feed. For Tool A at  $f = 0.2$  mm and  $v_c = 200$  m/min,  $R_a$  remained stable: 0.48  $\mu\text{m}$  (A01), 0.53  $\mu\text{m}$  (A07), 0.49  $\mu\text{m}$  (A10). Furthermore,  $R_z$  values were: 3.78  $\mu\text{m} \rightarrow 4.36 \mu\text{m} \rightarrow 3.66 \mu\text{m}$  (minor variation). Similarly, Tool B and C showed only minor differences across  $a_p$  levels at constant feed (for Tool C:  $R_a$ : 0.963  $\mu\text{m}$  (C01)  $\rightarrow$  0.92  $\mu\text{m}$  (C07)  $\rightarrow$  0.923  $\mu\text{m}$  (C10);  $R_z$ : 4.633  $\mu\text{m} \rightarrow 4.506 \mu\text{m} \rightarrow 4.516 \mu\text{m}$ ). These results indicate that  $a_p$  does not significantly alter the roughness profile, as the surface finish is dominated by the kinematics of feed marks and not by the depth of material removed. This behaviour confirms that the surface roughness is mostly generated by the feed motion and cutting edge geometry rather than the chip cross-section.

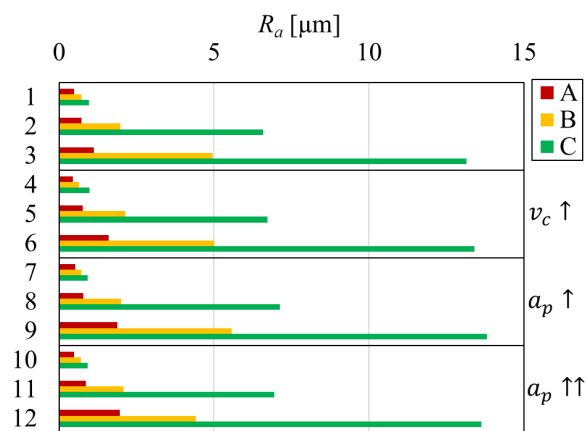


Figure 11. Arithmetic mean surface roughness ( $R_a$ ) values of the machined surfaces

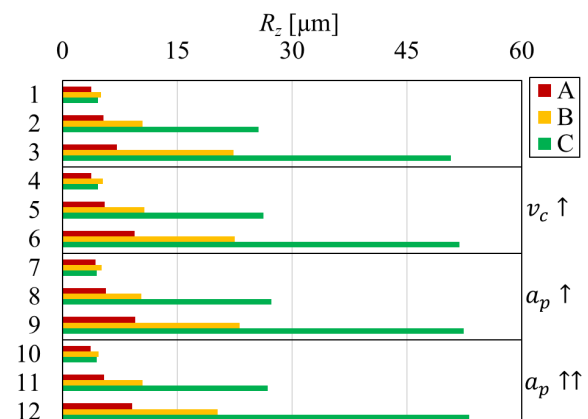


Figure 12. Maximum peak-to-valley height ( $R_z$ ) surface roughness values for each tool and cutting condition

Increasing the cutting speed had a slightly beneficial effect on surface roughness. For example, with Tool A at  $a_p = 0.1$  mm and  $f = 0.2$  mm,  $R_a$  dropped from 0.48  $\mu\text{m}$  (A01) to 0.446  $\mu\text{m}$  (A04) (−7.1%),  $R_z$  changed from 3.78  $\mu\text{m}$  to 3.796  $\mu\text{m}$ , essentially unaffected. Tool C showed a similar trend:  $R_a$ : 0.963  $\mu\text{m}$  (C01)  $\rightarrow$  0.976  $\mu\text{m}$  (C04) (+1.4%);  $R_z$ : 4.633  $\mu\text{m}$   $\rightarrow$  4.676  $\mu\text{m}$  (+0.9%). Overall, changing the cutting speed from 200 m/min to 250 m/min does not significantly affect surface roughness. Slight improvements are likely due to better chip softening and reduced built-up edge formation at higher speeds. However, this influence is minor compared to the overwhelming effect of feed rate.

The performance of the three tools with respect to surface roughness was notably different, especially at high feed values. At Setup 03, the following values were measured:  $R_a$ : Tool A: 1.123  $\mu\text{m}$ , Tool B: 4.953  $\mu\text{m}$ , Tool C: 13.143  $\mu\text{m}$ ;  $R_z$ : Tool A: 7.103  $\mu\text{m}$ , Tool B: 22.356  $\mu\text{m}$ , Tool C: 50.73  $\mu\text{m}$ . Tool A, the 30° rotational tool, delivered the best surface finish at high feed. Tool B (45°) produced significantly rougher surfaces, likely due to the more aggressive inclination and a less favourable chip exit path. Tool C performed the worst in terms of roughness at high feed, producing  $R_a$  values more than 11 times higher than Tool A in some setups. Even at moderate feed values ( $f = 0.6$  mm/rev), this trend persists. At  $a_p = 0.2$  mm the  $R_a$  values were: Tool A: 0.78  $\mu\text{m}$ , Tool B: 1.996  $\mu\text{m}$ , Tool C: 7.13  $\mu\text{m}$ ; and the  $R_z$  values were: Tool A: 5.663  $\mu\text{m}$ , Tool B: 10.286  $\mu\text{m}$ , Tool C: 27.276  $\mu\text{m}$ . This confirms that rotational turning offers superior surface quality at raised feeds. The inclined cutting edge and tool motion of the rotational tools result in overlapping paths that reduce peak heights and flatten valleys, leading to smoother surfaces. Additionally, the variation between the three  $R_a$  and  $R_z$  measurements per setup was low (standard deviation <10% in most cases), indicating good repeatability in all cases.

The analysis of the surface roughness across the different setups revealed the following results. Feed rate has the greatest impact on  $R_a$  and  $R_z$ , with higher feed drastically increasing roughness. Depth of cut and cutting speed have minimal effects on surface finish in this range. Rotational turning, especially with Tool A, enables lower roughness values, even at high feed. Tool B produces moderate roughness, while Tool C results in significantly rougher surfaces, particularly as feed increases. The surface roughness results validate the application of rotational turning tools in high-feed operations where surface quality is still required. These tools make it possible to combine high productivity with acceptable or superior surface finish, offering a substantial advantage in industrial applications.

#### 4.5 Energy Efficiency in Relation to Achieved Surface Roughness

In addition to analysing cutting forces and roughness independently, a more integrated view of energy efficiency can be obtained by examining how much energy is required to produce a surface with a given quality. By comparing the total mechanical work done ( $W_t$ ) during cutting to the resulting surface roughness

values ( $R_a$  and  $R_z$ ), valuable insights can be drawn about the process efficiency of each tool type. Although longitudinal turning with Tool C frequently resulted in the highest  $W_t$  values, it also produced the roughest surfaces, especially at higher feeds. For example, in Setup C03, where the feed was 1.0 mm/rev and the cutting speed 200 m/min, the resulting  $R_a$  was 13.14  $\mu\text{m}$  and  $R_z$  reached 50.73  $\mu\text{m}$ , while the work done was 431.9 J. While this setup seems efficient in terms of energy per micrometre of roughness, the actual surface finish is far beyond acceptable in most technical applications. In contrast, Tool A, representing the 30° rotational turning variant, achieved significantly better surface finishes with only somewhat lower energy input. At Setup A03, with the same feed and cutting speed, the surface roughness was reduced to 1.12  $\mu\text{m}$   $R_a$  and 7.10  $\mu\text{m}$   $R_z$ , with a comparable work input of 419.4 J. This means that roughly the same energy was used to produce a surface that was over ten times smoother in terms of  $R_a$ . Tool B, with a 45° inclination, produced intermediate results both in terms of energy and surface finish. In Setup B03, the work done was slightly lower than Tool A (411.6 J), but the surface roughness was significantly worse at 4.95  $\mu\text{m}$   $R_a$ . These results suggest that from an energy-per-quality perspective, Tool A delivers the most favourable balance when moderate or good surface finish is required, while Tool C, despite sometimes appearing efficient in a mathematical sense, does not provide surfaces of sufficient quality. Therefore, rotational turning – especially with a lower inclination angle – allows not only for higher productivity but also better energy efficiency in achieving technical surface requirements, making it an advantageous choice for applications that demand both performance and sustainability.

## 5. CONCLUSION

This study presents a comparative investigation of rotational and longitudinal turning processes, focusing on energy efficiency and surface roughness during the machining of normalized medium-carbon steel shafts. Machining energy and surface quality are critical parameters in modern manufacturing, as they directly impact both process sustainability and the functional performance of components. The primary goal of this research was to evaluate how the use of rotational turning tools with different inclination angles (30° and 45°) influences cutting forces, specific cutting forces, total work input and resulting surface roughness, compared to conventional longitudinal turning. The experimental methodology involved machining 40 mm diameter, 12 mm long normalized C45 steel workpieces under controlled cutting conditions. Depth of cut, feed per revolution, and cutting speed were systematically varied, producing twelve experimental setups for each tool. Cutting forces in tangential, axial, and radial directions were recorded using a three-component dynamometer, and the total work done, as well as specific cutting forces, were calculated from these measurements. Surface roughness was evaluated both in terms of arithmetic mean roughness and peak-to-valley height, using a combination of 2D and 3D surface measurement techniques.

The results demonstrate clear trends in the relationship between tool geometry, cutting conditions, energy consumption and surface finish. Rotational turning with a 30° inclination achieved the best balance between low energy consumption and acceptable surface quality, particularly at moderate-to-high feeds. Rotational turning at 45° increased productivity but at the cost of higher  $R_a$  values for the same energy input. Longitudinal turning consistently produced rougher surfaces, and although the energy per unit roughness sometimes appeared lower, the absolute surface quality was insufficient for most technical applications. Analysis of specific cutting forces confirmed that rotational turning reduces cutting load in all directions compared to conventional longitudinal turning, contributing to improved energy efficiency.

The three main findings that highlight the novelty of this work are:

- Rotational turning can significantly reduce specific cutting forces while maintaining or improving surface quality.
- The energy required to produce a given surface roughness is lower with rotational turning than with longitudinal turning.
- The tool inclination angle has a measurable impact on the energy–surface quality interaction, which can guide process optimization.

The findings of this study are relevant to a wide range of engineering applications in which cylindrical steel components are produced in high volume, such as in automotive shafts, power-transmission elements, and general-purpose machine components. In such production environments, even marginal improvements in energy consumption or achievable surface quality translate into significant economic and environmental benefits. Rotational turning is emerging as a promising process variant, but its practical capabilities and limitations remain insufficiently characterized. By providing experimentally validated data on energy demand and surface finish across realistic industrial cutting parameters, this work delivers engineering-useful guidance for selecting tool geometry, inclination angle, and cutting conditions. The results enable practitioners to reduce machining energy, increase productive feed rates, and achieve target roughness levels more reliably. Thus, the study contributes both scientifically—by clarifying process mechanics—and practically—by supporting informed decision-making in process planning.

Future research could extend these findings by exploring additional inclination angles, investigating other workpiece materials or hardened steels, analysing microstructural effects of rotational turning, and integrating the results into predictive models for energy-efficient process planning. Furthermore, the combined influence of lubrication conditions and tool wear could be assessed to develop guidelines for sustainable high-performance turning operations.

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**КОМПАРАТИВНА СТУДИЈА РОТАЦИОНОГ И  
УЗДУЖНОГ СТРУГАЊА: ЕНЕРГЕТСКА  
ЕФИКАСНОСТ И ХРАПАВОСТ ПОВРШИНЕ  
ПРИ ОБРАДИ НОРМАЛИЗОВАНОГ  
СРЕДЊЕУГЉЕНИЧНОГ ЧЕЛИКА**

**И. Станкович, Д. Родић**

Ова студија упоређује ротационо и уздужно стругање током обраде нормализованог средњеугљеничног челика. Циљ је да се процене разлике у енергетској ефикасности и квалитету површине. Тестирана су три алата: два ротациона стругарска алата са угловима нагиба од  $30^\circ$  и  $45^\circ$  и конвенционални уздужни стругарски алат. Извршено је тридесет шест експеримената резања уз различите дубине резања, помака и брзине резања. Силе резања су мерене у три правца и коришћене за израчунавање специфичних сила резања и укупног механичког рада. Храпавост површине је процењена

коришћењем параметара аритметичке средње храпавости и максималне висине од врха до дна. Резултати показују да ротационо стругање, посебно са нагибом од  $30^\circ$ , смањује специфичне силе резања и омогућава мању потрошњу енергије уз упоредиву продуктивност. Такође пружа бољу завршну обраду површине при средњим и високим помацима. Уздужно стругање је генерисало прихватљиве нивое енергије, али је произвело знатно храпавије површине. Резултати истичу улогу нагиба алата у побољшању интеракција између енергије и квалитета површине.