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Original Article

Effect of Cutting Tool Rake and Inclination Angles and Feeding Method on Cutting Force and Surface Quality in Single-point Threading

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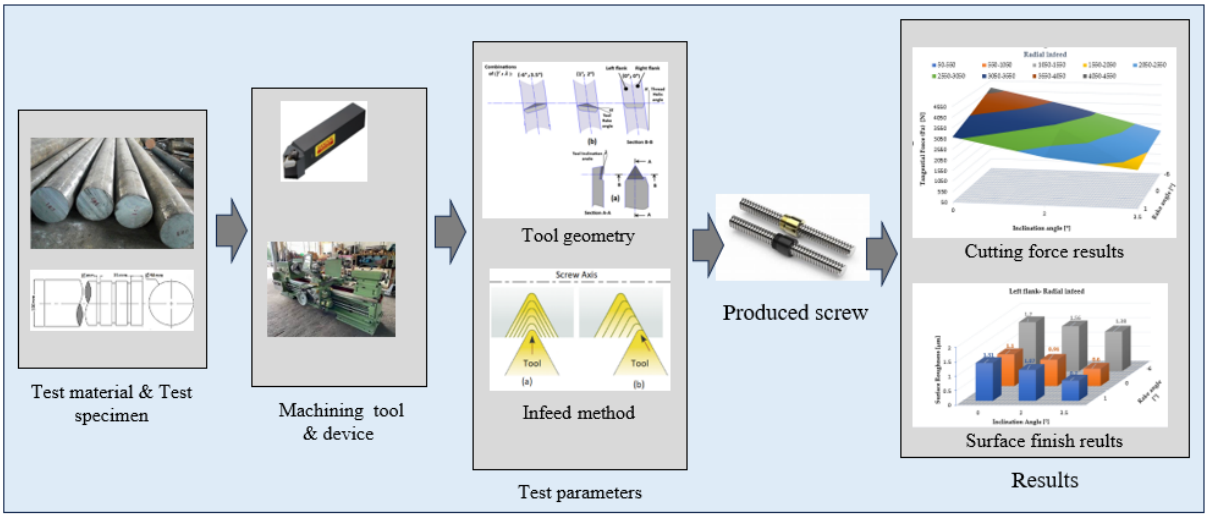
Abstract: Single-point threading is the most common and useful thread machining technique. It is mostly applicable in situations which require threaded pieces with certain diameters and high quality on low machinability materials. The process has problems of surface quality and power consumption because of lack of information regarding the effect of the tool's rake and inclination angles and feeding method on surface quality and cutting forces as a function of cutting power. This study investigates influences of tool infeed method, rake, and inclination angles on surface quality of thread flanks and the cutting forces generated. Three levels of 0°, 2°, and 3.5° as well as -6°, 0°, and 1° were considered for tool inclination and rake angles, respectively, with the two most common tool infeed methods of radial and flank infeed. Accordingly, eighteen tests were conducted by cutting metric screws of 5 mm thread pitch and triangular profile on ST45 carbon steel bar. The cutting speed, number of cutting passes, and infeed amount in each pass were maintained constant during each test. The threads were cut by P-10 type carbide insert on a test rig that involved a medium-sized lathe. Results presented that the highest inclination angle of 3.5° produces lowest surface roughness of about 0.5 µm and 0.45 µm and cutting force of 1850 N and 2200 N in the radial and flank infeed methods, sequentially. Also, a rake angle of 0° provides better and more equal surface finish on the both thread flanks. A high productive approach for the single-point threading with high quality was deduced.

Graphical Abstract



1. Introduction

Screws are essential mechanical components that have external helical threads, allowing them to fasten, tighten, or move forward and backward through axial rotation. They are commonly used to connect machine parts, convert rotary motion into linear motion, or increase load capacity. There are several manufacturing techniques available for producing screw threads. One of the most common screw thread manufacturing methods is single-point threading, which is a highly useful thread cutting technique in situations where only a few threaded pieces with high accuracy and quality on certain diameters are required, such as unavailable replacement parts or specialized one-of-a-kind machinery [1-4]. Single-point threading on a computer numerical control (CNC)- equipped lathe proves to be extremely beneficial and has seen significant improvements and greater efficiency with the advent [5]. That is because the CNC machines allow operators to input pre-packaged programs of endlessly repeatable instructions to produce a nearly constant stream of screws [6]. Feeding the tool into the workpiece in single-point threading differs from that in normal turning and significantly impacts the produced thread characteristics. In the threading process, the tool can be fed perpendicularly to the workpiece axis in the direction of the thread depth, which is known as radial infeed, or parallel to the right thread flank at an angle equal to half of the thread angle, known as flank infeed. Alternating flank infeed has all the advantages of flank infeed, however, it is rarely used because of cumbersome programming [7].

Threads with high accuracy, which are applied widely in burdened mechanical joints, have to be manufactured with materials that cannot be machined easily. These materials require utilizing machining tools with high performance and specific angles of inclination and rake. Therefore, numerous studies have examined the process of screw turning, focusing on economy and productivity. For example, Günay [3] and Nalbant *et al.* [8] investigated the impact of infeed angles on surface quality and cutting force components during external single-point threading. Results of the experiments indicated that the angle of infeed as well as the uncut chip area significantly influence the principal force of cutting; the infeed force plays a significant role in energy consumption. Also, their findings revealed that microhardness increases from the thread crest to the thread root along the flanks and the optimal angle of infeed for outside threading is 30°. Numerous experimental and analytical studies have been conducted to enhance the machined surface during various machining processes. The findings indicate that selecting appropriate machining conditions and tool geometries leads to optimal surface quality [9-11]. Accordingly, various studies [12-14] have highlighted the importance of tool nose geometry, including the nose radius and nose angle, in different surface machining processes. They found that a 60° nose angle and a large nose radius significantly improve the surface finish.

Koleva *et al.* [15] investigated cutting with the total and partial profile machining inserts. Depending on the machine tool probing and tool measurement, they suggested a new technique for testing the profile of the cut thread and compensating its variation due to formation mechanically. The technique is applicable to all the outside or inside threaded surface types. Additionally, for processing accurate threads with high productivity and lowest wear of the tool Costa *et al.* [16] investigated the influence of radial, flank, and incremental infeed methods on the tool age, hardness of the thread flanks, and the produced heat during threading AISI 304L steel by turning. They used infrared thermography for temperature measuring. Results presented significant increase of temperature with increase of tool wear. Tool age depends on the high worn of the tool nose, which deviates the profile of the thread. The incremental infeed produces threads with lower hardened surface depth and larger tool age.

The impact of feed rate and rake angle on machining forces was studied by Pradeesh *et al.* [17] during turning with a single point machining tool. Results show that the cutting forces increase with an increasing of feed rate and a decreasing rake angle, while the best rake angles are 120° and 160°. Moreover, Gunay *et al.* [18] investigated the influence of machining speed and rake angle on the main cutting force (Fc) during machining AISI 1040. Results show that the principal cutting force reduces when the angle of rake rises positively. Also, they deduced a deviation of 10-15% between the empirical approach and experiments. Additionally, Baizeau *et al.* [19] studied experimentally and numerically the effect of edge preparation and the rake angle of the tool on the subsurface displacement field by measuring the compressive deformation in the primary shear zone. They utilized a camera with two frames and a neodymium-doped yttrium aluminum garnet pulsed laser to record images during cutting hard steel orthogonally by cubic boron nitride tool. The experimental results validated the outcomes of the numerical simulations of cutting for improving the hybrid modelling of surface integrity.

Different researches have been performed to improve machining quality of tapered thread joints used in drill pipes. For instance, Onysko *et al.* [20] performed a geometric model for the inclination angle of the thread cutter profile. Utilization of an algorithm confirmed that the profile of the thread sides made by a non-zero inclination angle cutter is actually curved. Also, they determined that a cutter with usual machining edge profile and back rake angle of 12° causes an error of 3–10% in the side half profile angle, while the quality of tapered thread joints used in drill pipes depends on the cutter rake angle for every point of the thread profile. Onysko *et al.* [21] presented a kinematic to compare between the theoretical specified and real threads during machining with cutting tools of non-zero rake angle. They concluded an algorithm that allows calculating the variation of the screw line axially depending according to the rake angle and the cutter size. On the other hand, Medvid *et al.* [22] studied theoretically the impact of the inclination and rake angles on the pitch accuracy of a tapered thread made on hard steel. Results proved a significant influence of combined rake and inclination angles of 12° and 3,74°, respectively, on the thread profile accuracy.

Thereafter, Onysko *et al.* [23] examined the influence of inclination and thread helix angles on the accuracy of the pitch diameter of tapered threads. The results show that the accuracy of pitch diameter rises with the increase of the tools' helix and rake angles. This change will be more apparent for the small size tool-joint tapered threads and zero for the largest drilling tool-joint tapered threads. Moreover, Onysko *et al.* [24] performed a study to facilitate cutting drill-string tool-joint threads (cylindrical and conical thread with standard triangular shape profile) on the surface of especially difficult-to-machine materials. They applied the technique of analytic geometry to describe the thread profile theoretically as spiral surfaces that depend on the angles of the tool. They conducted the experiments by using a visual algorithm based on the obtained function. Results predicted that cutters of up to 12° rake angle can obtain accurate threads.

Previous review shows various researches have been performed for improving the quality of machined joints with tapered thread that are utilized in well drill pipes. The effects of cutter rake angle, thread helix angle, and infeed techniques were studied separately to provide algorithms that facilitate producing correct side half profile and guarantee the precise cutting of the spiral tapered thread. There is lack of information, however, regarding the combined influence of the tool infeed and its geometries of rake and inclination angles together on surface quality and cutting forces in single point tool threading.

The current research aims to assess the impact of the infeed method, tool rake, and inclination angles as independent research parameters on the surface quality of thread flanks and the produced cutting forces as the dependent variables of the research during single point tool threading. Additionally, this study focuses on specifying the best combination of the considered factors that provides the best conditions to cut screws with high surface quality and lowest cutting force, which means lower cutting power consumption. Three different levels were considered for each of the tool's inclination and rake angles with two infeed methods of radial and flank. Accordingly, eighteen tests were performed: nine tests for each infeed method. During each test, a special 5 mm pitch and 3.38 mm depth thread was cut on a prepared sample on an ST45 alloy steel bar with a P-10 carbide tool. The proposed dependent response data are the quality of the produced thread surface flanks and amount of the produced cutting forces during thread machining at constant stroke number, feed at each stroke, and cutting speed.

2. Materials and Method

2.1. Test Sample and Cutting Tool

Steel bars of 100 mm diameter and medium carbon type ST45 were utilized for preparing the test samples according to the dimensions illustrated in figure 1. The chemical composition and hardness of the sample material is shown in table 1. Triangle carbide insert of TPUN type, 0.8 mm nose radius, and 60° nose angle with a turning shank tool bit of Sandvik T-Max S type, CTTPR 2525M I6 specifications, zero rake and inclination angles were applied in this study, as seen in figure 2. Approximately 1.5 mm of the front right support shoulder of the tool nest at the front of tool holder was ground down to enable cutting the desired radial thread depth of the proposed right-hand screw.

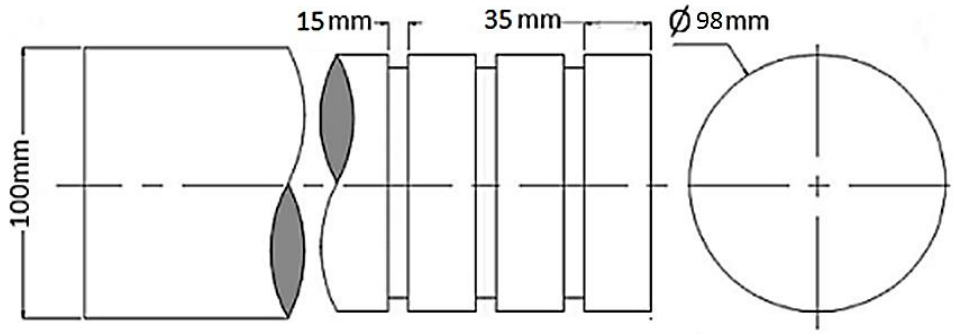


Figure 1: Test sample dimensions.

Table 1: Chemical composition and hardness of the workpiece material.

Material	%C	%Cu	%Cr	%Mn	%Si	%Ni	Hardness (HV)
ST 45	0.442	0.3	0.88	0.528	0.19	0.34	224

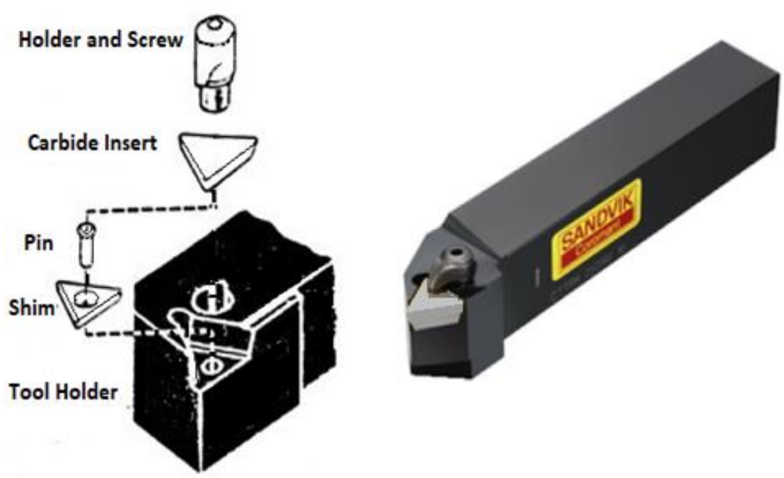


Figure 2: Utilized insert and shank.

2.2. Test Procedure

To assess the impact of the proposed parameters—specifically the tool infeed method, rake angle, and inclination angle—on the surface quality of thread flanks and the cutting forces generated, as shown in table 2, three levels were considered for both the rake angle and the inclination angle. Additionally, two of the most common infeed methods, radial and flank, were proposed for the tool infeed.

Table 2: Test variables and their levels.

Rake angle (γ)	Inclination angle (λ)	Feeding method
1°	0°	Radial infeed
0°	2°	Flank infeed
- 6°	3.5°	-

Accordingly, eighteen test trials were designed, consisting of nine combinations of rake and inclination angles for each infeed method. The degrees of the angle levels were proposed in accordance with the existing angles of the tool holder and the proposed thread helix angle, as demonstrated in figure 3.

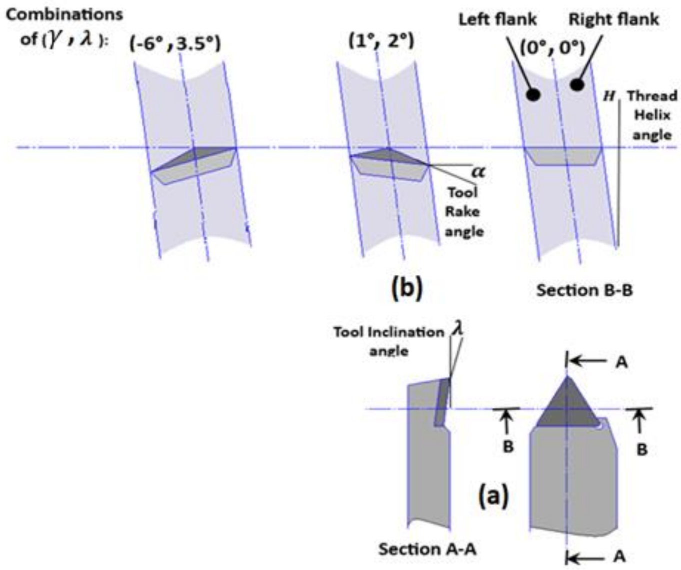


Figure 3: **(a)** tool geometry and (b) three combination examples of the proposed rake and inclination angles.

A special metric thread of 5 mm pitch, 3.53 mm depth, 60° thread angle, and 98 mm maximum diameter, as shown in figure 4, was selected to cut during the tests. The proposed dimensions of the chosen screw were considered according to the dimensions of the utilized insert.

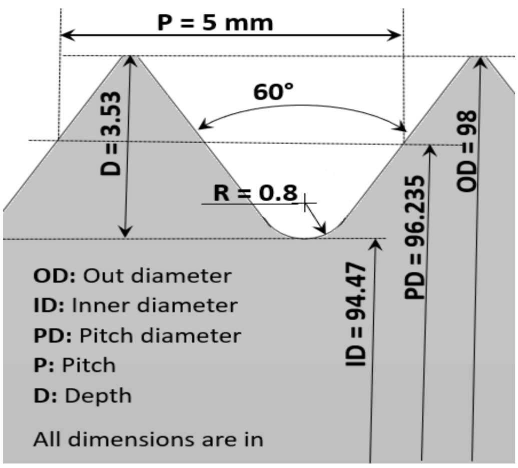


Figure 4 : The proposed screw thread dimentions (all dimensions are in mm).

The cutting parameters of speed and radial feed were kept constant in all tests at 84 m/min and 0.4 mm/stroke (equivalent to 0.46 mm in flank), respectively. They were selected according to results of pre-experimental tests. After conducting the eighteen test trials the influences of the proposed variables on each of the surface quality of the produced thread flanks and generated cutting forces, which significantly impact the power consumption, are recorded in tables 3 and 4, respectively. Each test was repeated at least three times to ensure the correctness of the achieved results.

2.3. Test Rig

All the designed eighteen threading tests were performed on the test rig illustrated in figure 5, which involves a medium-sized Czechoslovak lathe type SN50B TOS, with a power of 5.5 Kw, a speed range of 22.5 to 2000 rpm and a feed range between 0.05 to 6.4 mm/rev. Figure 6 illustrates the tool infeed methods of radial and flank during the tests by single point threading operation. The lathe bar capacity and its maximum distance between the centers are 250 mm and 1500 mm. Various calibrations and repairing were achieved to the lathe machine for ensuring the accuracy of the machine and the obtained experiment results.

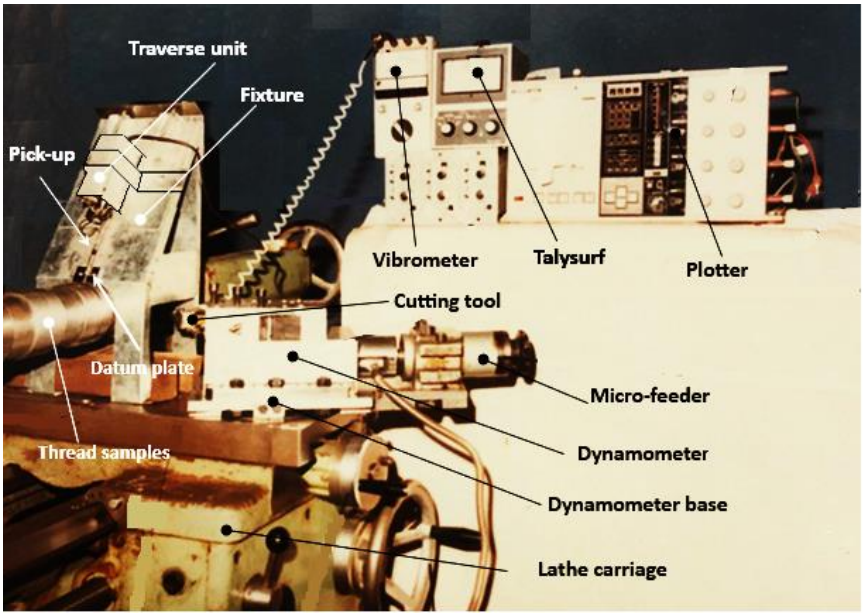


Figure 5: Designed eighteen threading tests performed by the Test rig.

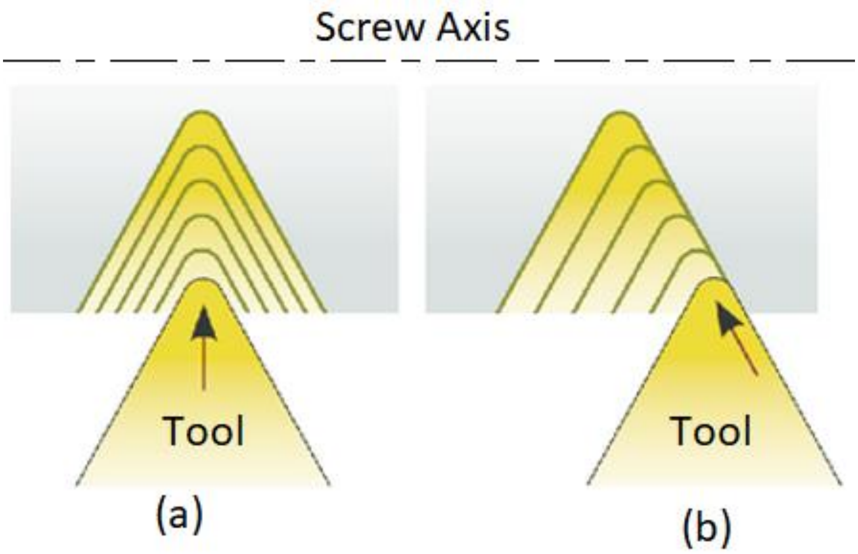


Figure 6: Utilsed infeed methods (a) Radial and (b) Flank.

A Swiss-made electrical dynamometer, type 9265A1 Kistler was used for measuring the machining loads in the directions of X, Y, and Z. The cutting tool vibration was monitored during the tests by a German HBM-type vibrometer. This device was connected to a plotter to record and plot the graph of the generated vibrations during the tests; when the vibration levels became more than 2.5 mm/sec (rms) the test was stopped and repeated. A portable Danish roughness meter of Taylor-Hobson Talysurf type AII/1245-611598 was applied for measuring surface roughness of the produced thread right and left flanks. A special fixture, shown in figure 7, was designed to securely hold and position the Talysurf device and enable it to measure the roughness of the inclined screw flanks. All devices were checked and calibrated before use to ensure data accuracy during the experiments. Dimensions of the produced screw elements, including pitch, depth of cut, and thread angle, were checked after each test to ensure the accuracy of test performance.

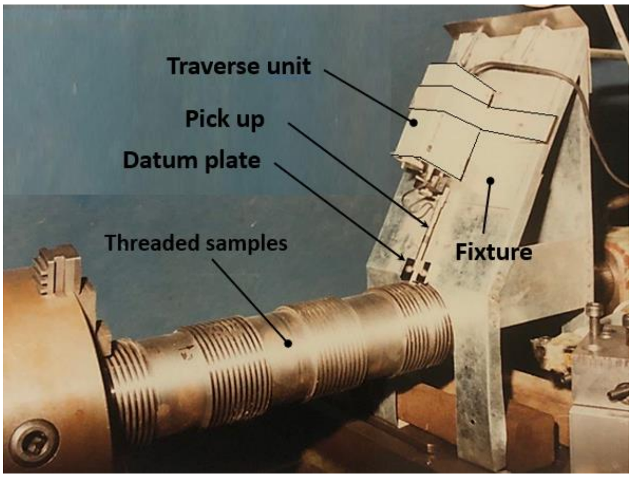


Figure 7: Designed fixture to roughness meter.

3. Results

In this study, various screw samples were produced using a single-point threading technique with radial and flank infeed methods, applying different rake and inclination angles. The dimensional accuracy of the produced screws was checked to ensure the success of the test, the surface quality of the screw flanks, and the generated tangential forces (Fz) were measured. Tables 3 and 4 present the results of generated Fz and surface roughness of the right and left screw flanks. These results were obtained after the fifth stroke at which the cutting depth was 2 mm.

Table 3: Test results of the cutting force after the 5th stroke at depth of 2 mm.

Feeding method	**Rake** \ **Inclination**	**Fz: tangential force [N]**		
		0°	**2°**	**3.5°**
Radial	1°	3120	2300	1850
	0°	3626	2950	2090
	- 6°	4200	3320	2228
Flank	1°	2600	2389	2200
	0°	2789	2570	2300
	- 6°	2910	2695	2469

Table 4: Test results of the surface finish after the 5th stroke at depth of 2 mm.

Feeding method	**Rake** \ **Inclination**	**Right flank [μm]**			**Left flank [μm]**		
		0°	**2°**	**3.5°**	**0°**	**2°**	**3.5°**
Radial	**1°**	1.18	0.7	0.68	1.31	1.07	0.7
	0°	0.93	0.64	0.5	1.1	0.91	0.6
	- 6°	1.3	1.2	1.1	1.7	1.56	1.38
Flank	**1°**	0.71	0.63	0.64	*psf	psf	psf
	0°	0.7	0.6	0.45	psf	psf	psf
	- 6°	0.9	0.8	0.65	psf	psf	psf

*pfs represents “poor surface finish”.

3.1. Cutting Force

The produced Fz in the fifth stroke during the radial and flank infeed methods is affected by inclination and rake angles, as shown in figures 8 and 9.

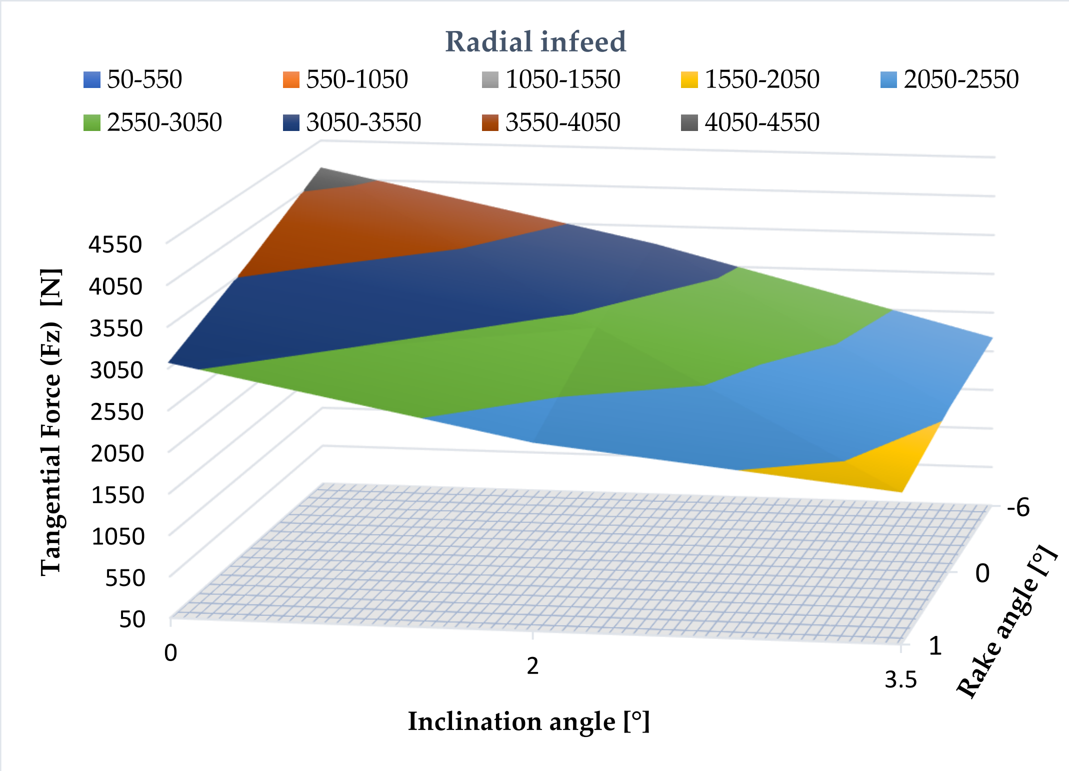


Figure 8: Effects of inclination and rake angles on the tangential force (Fz). 5th stroke, Radial infeed, V = 84 m/min, and feed = 0.4 mm/stroke.

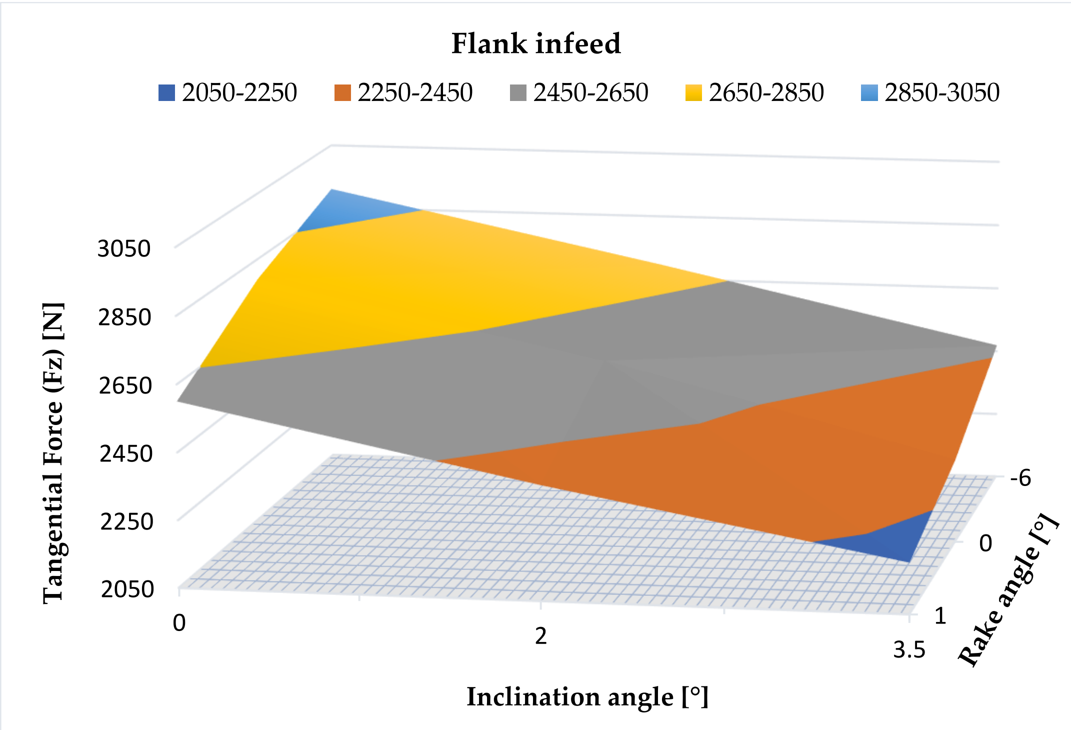


Figure 9: Effects of inclination and rake angles on the tangential force (Fz). 5th stroke, flank infeed, V = 84 m/min, and feed = 0.46 mm/stroke.

3.2. Surface Roughness

The surface roughness of the right and left flanks of screws produced, using the radial infeed technique, is shown in figures 10 and 11. The difference in roughness between the two flanks is noticeable; in most cases, the left flank is smoother than the right.

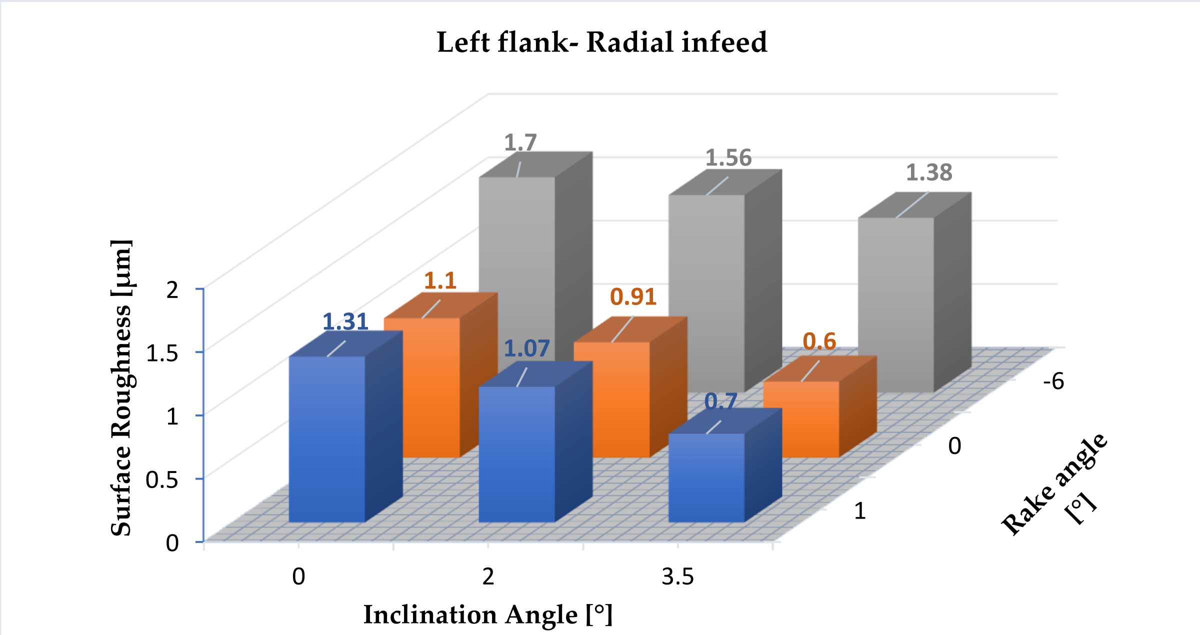


Figure 10: Effects of inclination and rake angles on the roughness of left flank. Radial infeed, V = 84 m/min, and feed = 0.4 mm/stroke.

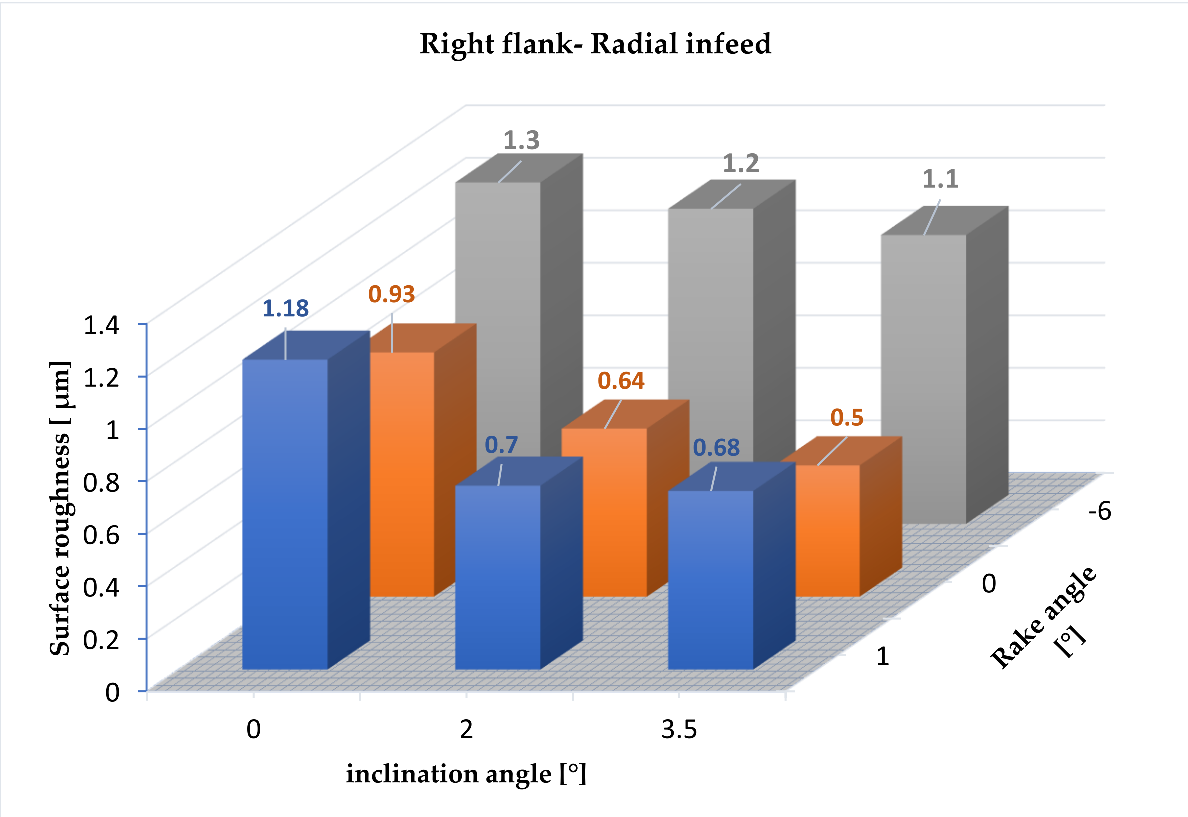


Figure 11: Effects of inclination and rake angles on the roughness of right flank. Radial infeed, V = 84 m/min,and feed = 0.4 mm/stroke.

Figure 12 shows the poor surface quality of the left flank face of the screw thread produced by flank infeed technique. Also, the roughness of the right flank of the screw cut by flank infeed under the effect of tool's inclination and rake angles is presented in figure 13. Moreover, the built-up edge (BUE), as presented in figure 14, was formed on the right cutting edge of the single point tool during radial infeed threading.

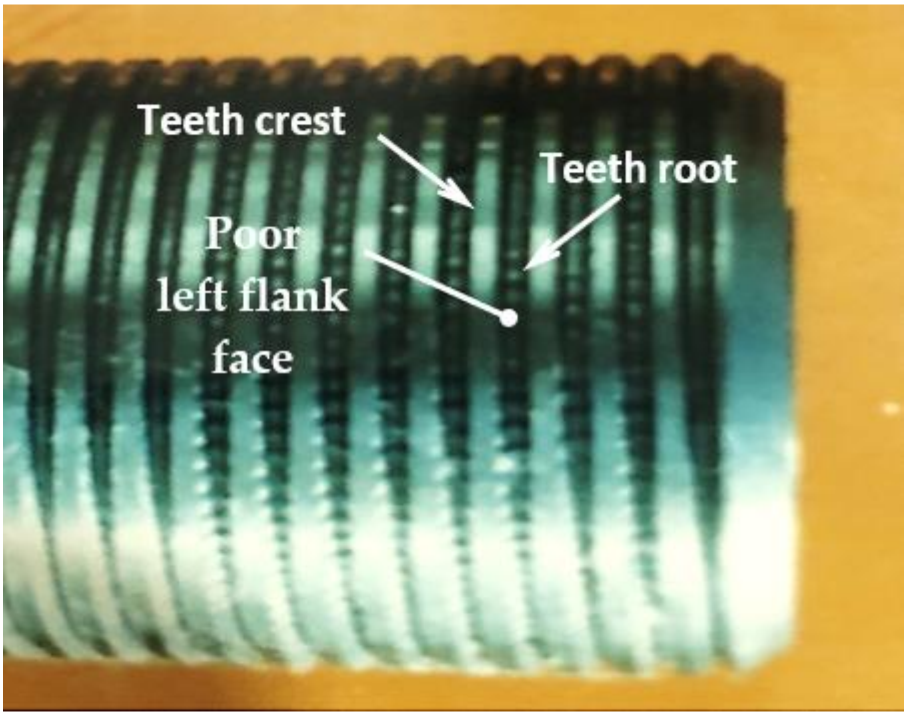


Figure 12: Poor surface of the right flank of the screw produced by flank infeed.

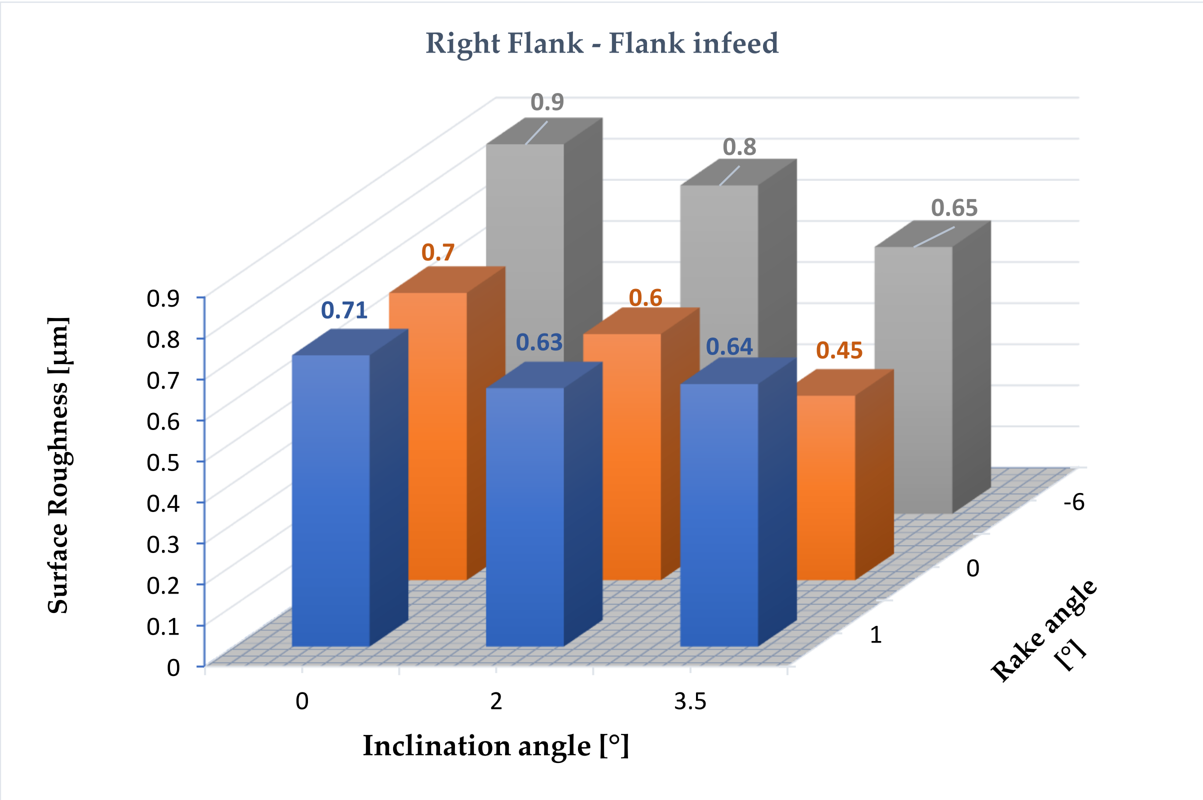
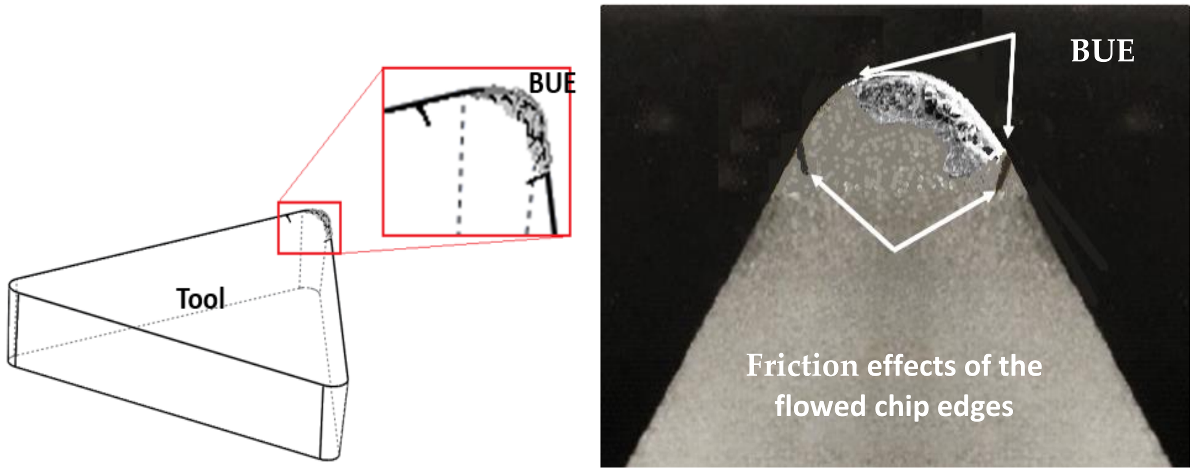


Figure 13: Effects of inclination and rake angles on the roughness of right flank. flank infeed, V = 84 m/min, and feed = 0.46 mm/stroke.



A B

Figure 14: BUE formation on the tool cutting edge. radial infeed $\lambda = 2°$, $\gamma = -6°$, V = 84 m/min, and feed = 0.40 mm/stroke. A) schematic, B) actual

4. Discussion

A comparison was made between the radial and flank infeed methods based on evaluating the experimental results of surface quality of the produced screw flanks, and amounts of the generated Fz forces, which are functions of the consumed machine power. It was found that the generated Fz force decreases with an increase in rake (γ) and inclination (λ) angles, especially during flank infeed, where cutting predominantly occurs via the left cutting edge. That is because the increase in rake angle (γ) results in a higher shear angle (ϕ), which subsequently reduces the cutting force and specific cutting pressure, as mentioned in recent studies [1, 4]. Moreover, an increase in the inclination angle leads to a greater slope of chip flow, also known as the flow angle, from its path perpendicular to the cutting edge according to [17]. This change results in an increase in the in-plane components of the Fz, which helps the chips flow out of the cutting area more effectively.

Accordingly, it can be concluded that the optimal combination of the tool's rake and inclination angles, which result in the lowest cutting forces, involves utilizing their optimal positive values. For example, a rake angle of 0°and an inclination angle of 3.5° are ideal in the current study. Cutting power is a function of cutting force and velocity, which directly changes with their variations. Thus, the findings of this study indicate that reducing cutting force also decreases power consumption, while the velocity remains constant.

Furthermore, the results indicate that surface roughness increases as the λ decreases. In addition, the optimal γ of the tool needed to achieve similar roughness on both flanks should be equal to (0°), which is compatible with the handedness of the screw. That is because, in the radial single-point threading technique, the right and left cutting edges of the tool are engaged simultaneously. Additionally, the results indicate that the lowest surface roughness, as shown in figures 10 and 11, was achieved with a combination of 0° and 3.5° for the rake and inclination angles, respectively. This is because the inclination angle is the largest, and the rake angle is closest to the inverse of the helix angle, which equals 1°.

On the other hand, despite cutting both flanks under identical conditions in radial infeed, results showed a significant difference between their roughness. The right flank, in all cases, was smoother than the left because of built-up edge formation at the left cutting edge of the tool, as illustrated in Figure 14. Moreover, the poor quality of the left flank face produced by flank infeed, see table 4 and Figure 12, is due to friction of the generated chip with this flank before flowing out. Also, it can be deduced that the roughness of the right flank face cut by flank infeed is totally lower than that by radial infeed, despite that they are performed in similar conditions. This is because, in flank infeed, chip formation is more free-flowing than in radial infeed.

The results indicate that the highest surface roughness was observed when the inclination angle was zero and when the rake angle was (-6°) less than screw helix angle (1°). This is because this condition leads to the formation of BUE, as illustrated in Figure 14. This BUE interferes with the actual cutting edge and negatively impacts the surface quality, as noted by [1]. The BUE size decreases with the positive increase of inclination and a rake angle compatible with the helix angle because they reduce chip restriction and facilitate the chip flow.

5. Conclusions

The single-point threading technique is the most prevalent manufacturing method used for producing screws. These screws are widely utilized for connecting components, converting rotary motion into linear motion, or enhancing load capacity in the machinery industry. However, the process still faces challenges with power consumption and the surface quality of the produced screw thread flanks. The lack of information in the existing literature prompted this research to investigate the effects of two common infeed methods—radial and flank—along with varying rake and inclination angles of the cutting tool. The study aimed to assess how these factors influence the surface quality of the produced thread screw and the cutting forces generated during machining toward defining the best combinations of the infeed method, rake, and inclination angles that provide the best surface finish to the produced screw thread while reducing the cutting force generated during machining.

Results show that lower cutting force reduces power consumption, higher cutting tool life, and lower production costs. Additionally, improved surface quality of the produced screw thread flanks leads to less screw thread wear, longer screw life, and more precise screw performance during utilization. Results concluded that the lowest cutting forces of 1850 N and 2200 N were recorded in the radial and flank infeed methods, respectively, at the highest inclination angle of 3.5°. Notably, the cutting force in the radial method was lower, even though the feed and speed remained stable. Also, the lowest surface quality recorded were 0.5 µm and 0.45 µm by the radial and flank infeed methods, respectively, which were obtained at the optimal combination of 0° rake and 3.5° inclination angles. Although, flank infeed offers a smoother surface finish, it is not the preferred method. This is because it only improves the right flank, while the left flank produces a poor result due to significant friction between the chip and that flank. Moreover, the surface roughness of produced right and left flanks by radial infeed are mostly equal and acceptable; therefore, it can be suggested to cut the final stroke by radial infeed during single point threading. Furthermore. the surface roughness increases with the decrease of inclination angle while the right flank is generally smoother in most cases and conditions.

Author contributions: Rzgar Mhammed Abdalrahman: Conceptualization, methodology, investigation, software, analysis, writing the original draft**. Sarkawt Rostam:** Data curation, validation, writing-review and editing, visualization. **Abdelhakim Deboucha:** Investigation, writing-review, visualization**.**

Data availability: Data will be available upon reasonable request by the authors.

Conflicts of interest: 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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