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Experimental and numerical studies on the flank wear during the thread milling; effect of infeed strategies in different cutting speeds

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Abstract

Thread milling is an alternative to tapping in which tool wear is one of the main limitations. Infeed strategies significantly affect tool wear, which has not been studied in previous investigations. Hence, current research studies the effect of infeed strategies (radial, modified flank, and incremental) on flank wear during thread milling considering different cutting speeds. According to FEM simulations, the incremental method led to the minimum tool temperature and the highest cutting length (tool life). According to experimental results, incremental and modified flank infeed methods improved tool life up to 340% and 80%, respectively compared to the radial infeed method in cutting speed of 48 m/min. Also, the incremental infeed method was superior in higher cutting speeds.

Keywords: Thread Milling; infeed; flank wear; cutting speed.

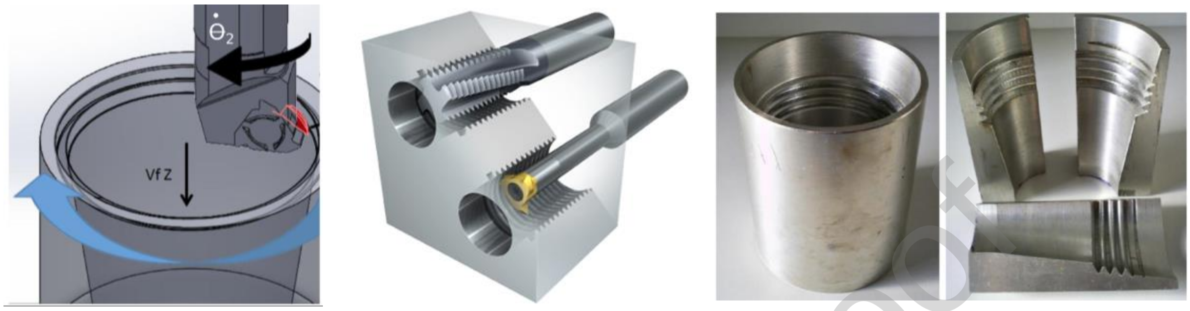
1 Introduction

Internal and external threads have wide applications in industries. Thread cutting and forming are some of the typical thread fabrication processes, especially for external threads. In the case of internal threads, technical issues limit the manufacturing process. Generally, internal threads are fabricated by the lathe, tapping, and thread milling. In thread machining using a lathe, the tool straightly moves while the workpiece is clamped in the spindle and rotates. Because of spindle and workpiece rotation, there are some limitations in the application of lathe. Tapping is a typical fabrication process of internal threads. Lack of chip removal, high engagement length, and shear force are some of the problems of tapping. Tool breakage is one of the known problems in tapping that increases the machining cost and time. Tapping is not flexible and the fabrication of different threads requires tool change.

Thread milling is an alternative to tapping for internal thread machining. Thread milling can use single-point or multi-point tools (Fig. 1-a & b). During thread milling, a tool with a diameter smaller than the hole diameter moves helically inside the hole and cuts the thread profile. This process includes three movements of tool holder rotation, tool straight, and lateral movements (results in helical tool path) while the workpiece is fixed. Details of tool movement are shown in Fig. 1-b. Fig. 1-c shows a sample of the threads fabricated by the thread milling inside the industrial scale pipe using a single-point tool. Thread milling has advantages as follows:

- Fabrication of threads on different hole diameters using a single tool.
- Fabrication of right-hand and left-hand threads using a single tool.
- Chip breakage and enough space to remove the chip.
- Short engagement length of the tool and workpiece (lower friction, forces, and tool wear)
- In the condition of tool breakage, simple hole evacuation without thread damage.

One of the critical issues during thread milling is tool wear. Excessive tool wear results in low surface quality and machining accuracy, increasing the probability of tool breakage and reduction of economic indicators.



(a) (b) (c)

Figure 1. Internal threads fabrication operations by Thread milling using (a) single-point (b) multi-point tools (c) a sample of internal thread fabricated on industrial scale pipe.

The primary results of the tool wear can be classified into three sections. First, the tool wear deteriorates the surface quality and accuracy of the machined part. In the fabrication process of highly accurate parts, tool wear should be controlled and tool change should be performed before a critical point. Second, tool wear in the final steps of wear suddenly increases and leads to tool fracture. Tool fracture can cause damage to the machine tool and workpiece. Third, the economic aspect of tools that can be re-sharpened.

In the development of predictive wear models, Feng et al. developed a theoretical model that included three main wear mechanisms including abrasion, adhesion, and diffusion during laser-assisted milling. The model focuses on the stress and temperature distributions on the wear land and evaluated cutting forces and contact area The model results were validated by experimental machining results of K24 nickel-based superalloy. The average model error was about 6.5% and sensitivity analysis proved the ability of the model to choose machining and laser parameters [1]. Other types of wear are also studied during laser-assisted milling [2, 3]. Feng et al. generalized the developed model to ultrasonic-assisted milling. According to the importance of tool-chip separation, they considered three types of separation according to the tool's instantaneous velocity and position. During the separation, there was no tool wear and during the contact, three mechanisms of the flank wear were employed. Validation experiments were carried out on the SKD 61 steel and the model presented the error of 11%. Results showed that vibration characteristics were less effective compared to the cutting parameters [4]. There are other investigations which considered other types of wear during ultrasonic-assisted milling [5, 6].

Araujo, et al. developed a mechanistic model to predict cutting forces during thread milling. The model was based on the end milling operation which evaluated forces from cutting specific energy. A comparison of validation experiments proved the acceptable accuracy of the model [7]. Also, Araujo et al. presented another model of cutting forces for thread milling in micro-scale. Considering the tool trajectory, chip thickness, and cutting forces were calculated and the specific cutting pressure of the micro-milling process was determined. This parameter was used to calibrate the mechanistic model according to experimental results [8].

Fromentin, et al. presented comprehensive studies on thread milling considering the tool geometry and cutting forces. They proposed a geometrical model to define the rake angle and cutting edge. In this regard, they were required to explain related planes which were the basis of the tool angles. They showed that the helix angle of the tool led to a variation of effective rake angle to negative values. This study determined the details of thread milling geometry and helped with the theoretical evaluation of the chip thickness as the key to the cutting forces evaluation [9]. In continue, un-deformed chip thickness was calculated and a fully analytical model was developed to predict the cutting forces of the thread milling. In this way, a simplified triangular shape of the thread was applied and the effect of the helix angle was considered in the model. Experiments have represented the validity of the developed model [10].

Wan, et al. studied the dynamic of the thread milling process. According to the variation of the chip thickness during the process, vibrations were expected which indicated the dynamic condition of the process. Process dynamic was modeled and solved in a semi-discrete time domain. The model was validated experimentally and the considerable effects of tool trajectory and geometry, cutting speed, and depth were proved [11].

Araujo and Fromentin studied the tool deflection during thread milling, especially in the case of small diameter holes. As a practical sample, they applied thread milling to the chrome-cobalt dental implant and studied forces, deflections, and undercutting. The tool axis was considered to evaluate radial force and bending deformation. They concluded that an extra tool revolution should be considered to remove uncut materials remaining because of the tool deflection [12].

Dong, et al. applied the thread milling on a corrosive material (Waspaloy). A theoretical model was established to predict tool wear during the thread milling. SEM images were used to validate the developed model. The model included milling parameters and tool angles. Based on the validated model recommended parameters of rotational speed, depth, and angles were determined to achieve the minimum tool wear [13].

Different texture shapes can applied on the tool surfaces during the threading. Different texture shapes can reduce friction significantly and lead to lower cutting forces. Between different shapes, the micro-grooved texture was determined as the optimum texture geometry [14, 15].

Dogrusadik, et al. developed a theoretical model to predict the thread profile. The validated model showed that the thread profile did not have a straight form. Curved thread profile found a slope smaller than cutting edge inclination [16]. In another research, Dogrusadik, et al. studied the effects of machining conditions and thread mill diameter on the tool temperature. Smaller tool temperatures resulted in higher tool life and economic benefits. Results determined the optimum tool diameter according to temperature parameters. Also, rotational speed and feed represented a direct relation to the cutting temperature [17].

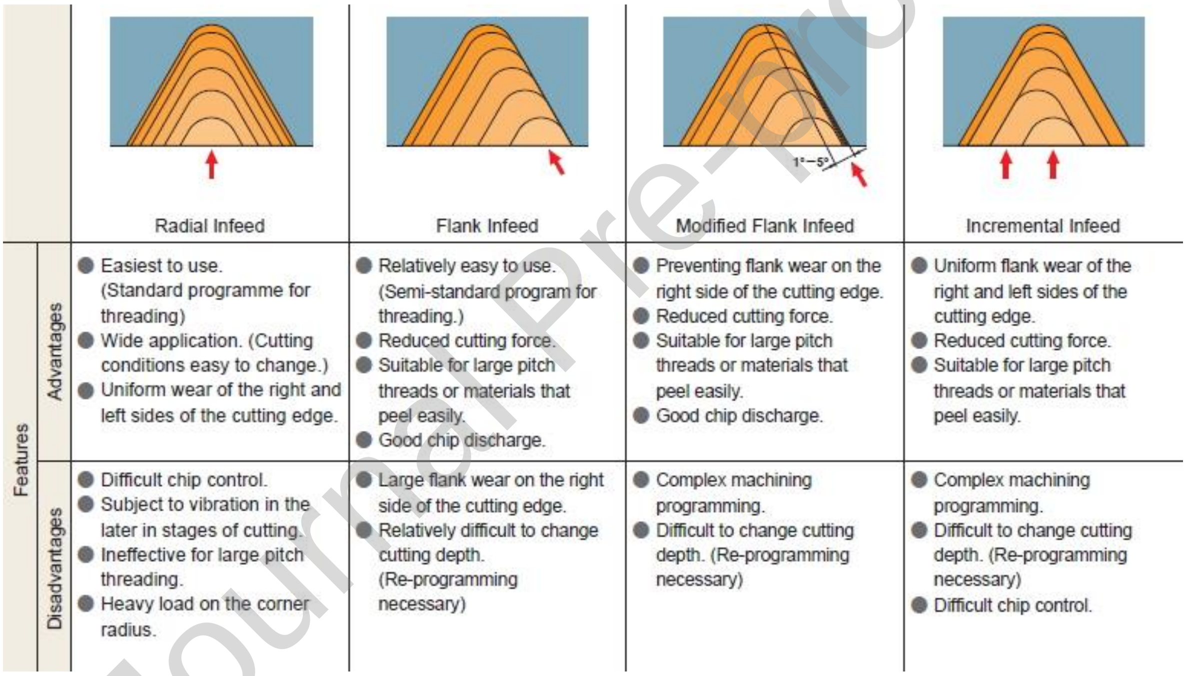
Dzulfikri, et al. developed a new method called drill thread milling. This process employed the integration of drilling and thread milling. Hence, the initial hole was not required and machining time was reduced compared to the tapping process. Cutting forces and vibration were measured and controlled. Intermittent cutting force indicated the possibility of vibration (chatter). Also, results showed that the developed process required smaller preliminary machining [18].

According to previous investigations, it is clear that most of them focus on machining characteristics such as force and surface specifications. Tool wear is an important phenomenon that can affect the two mentioned parameters significantly and has not been considered as the main target of the research. On the other hand, there are some strategies to cut thread profiles which change the tool wear behavior but have not been studied in recent years. Hence, current research focuses on the effect of infeed strategies on tool wear during the thread milling process. In this way, special tool path programming should employed which does not exist in commercial software for the tool path. Flank wear is considered as the indicator of tool wear which is excessively affected by the cutting speed, hence between machining parameters, cutting speed is considered to study besides machining strategies. Finite element simulation was employed to study the effect of strategies on the tool temperature and wear.

2 Theory of operation

2.1 Infeed plans in thread milling

During the thread milling and due to machine and tool limitations, depth can't be applied in a single pass. Hence, the final depth is achieved by employing a special plan for several cutting passes which is called an infeed plan. According to Fig. 2, there are three infeed plans and each of them has advantages and disadvantages. Radial infeed is the simplest plane that can be applied easily but results in high cutting forces and problems in chip removal from the machine tool. In the flank infeed plan, one side of the tool engages to the thread flank and better chip removal is available. In this plan, one of the cutting edges of the tool finds excessive wear however another edge remains unchanged. Also, a great contact time between the cutting edge (and one of the tool flank planes) and the workpiece leads to significant friction and decreases the thread surface quality. The Flank infeed plan is modified to reduce tool wear on the cutting edge; hence modified flank infeed plan is developed. This plan requires more complicated tool movement programming. In the incremental plan, the tool engages periodically to thread flank planes. This plan distributes cutting pressure and forces on two cutting edges; hence lower tool wear on each edge is expected. In contrast, this plan requires a more complicated tool path and CNC programming.



Features	Radial Infeed	Flank Infeed	Modified Flank Infeed	Incremental Infeed
Advantages	● Easiest to use. (Standard programme for threading) ● Wide application. (Cutting conditions easy to change.) ● Uniform wear of the right and left sides of the cutting edge.	● Relatively easy to use. (Semi-standard program for threading.) ● Reduced cutting force. ● Suitable for large pitch threads or materials that peel easily. ● Good chip discharge.	● Preventing flank wear on the right side of the cutting edge. ● Reduced cutting force. ● Suitable for large pitch threads or materials that peel easily. ● Good chip discharge.	● Uniform flank wear of the right and left sides of the cutting edge. ● Reduced cutting force. ● Suitable for large pitch threads or materials that peel easily.
Disadvantages	● Difficult chip control. ● Subject to vibration in the later in stages of cutting. ● Ineffective for large pitch threading. ● Heavy load on the corner radius.	● Large flank wear on the right side of the cutting edge. ● Relatively difficult to change cutting depth. (Re-programming necessary)	● Complex machining programming. ● Difficult to change cutting depth. (Re-programming necessary)	● Complex machining programming. ● Difficult to change cutting depth. (Re-programming necessary) ● Difficult chip control.

Figure 2. Infeed plans during the thread milling.

2.2 Tool Flank wear

Tool wear is one of the most important phenomena during the machining which determines the tool life and tool change intervals. Flank and crater wear are two main types of tool wear. Flank wear occurs on the flank plane of the tool and can be measured easily by an optical microscope. The main characteristic of the flank wear is the width of the worn area. Hence, this type of wear can be employed to predict tool life, practically.

Flank wear as a wear type is affected by three mechanisms of abrasion, adhesion, and diffusion. According to the wear mechanics, abrasion and adhesion mechanisms play a more important role in the variation of the flank wear.

Abrasive wear: The abrasion phenomenon includes the rubbing of hard particles on a softer surface. Hard particles may attach to one of the surfaces (two-body abrasion) or move as a free body between sliding surfaces (three-body abrasion). Hard particles find relative movement on the softer substance and remove a small amount of material from the surface which is defined as surface wear. It is possible to form hard particles which are harder than the tool surface materials and move between the tool rake plane and the chip surface. For instance, during the machining of steels and cast irons, cementite particles (Fe_3C) can form and lead to abrasion wear on the rake plane of the tool. In this condition, the three-body abrasion mechanism is dominant.

Prediction of the three-body abrasion can be stated by the following equation which was developed for the lapping process [19]:

$$dV_{ab} = \left(\frac{K_{ab}N}{K}\right)\left(\frac{P_a^{n'-1}}{P_t^{n'}}\right)\Delta x \tag{1}$$

In which K_{ab} and N are the abrasive wear constant and contact pressure. Δx is the contact length. K and n' are constants that are related to the ingredients' hardness ratio. P_a and P_t are the hardness of the hard particles and tool, respectively.

Hardness can be affected excessively by the temperature. The relations between a hard particle and one of the common tool coatings are as follows:

$$P_a = 11,772e^{-16.3\times10^{-4}\times T} \ \ N/mm^2 \quad \text{for } Fe_3C \qquad P_t = 23,000e^{-7.85\times10^{-4}\times T} \ \ N/mm^2 \quad \text{for } Al_2O_3$$

Adhesive wear: During the cutting process, high pressure is applied to the initial parts of the tool-chip contact area. As a result, some small-scale welds can appear on the tool rake face. Weld materials undergo excessive deformation and become harder. In this condition and because of chip movement, welds should be sheared in a softer area to allow the chip to move. There is the probability of initiating and extending shear phenomena to the tool which leads to tool material separation which is called adhesion wear. Adhesive wear depends on the workpiece and tool materials, temperature, and some other parameters as follows [15]:

$$dV_{ad} = K_{ad}(\frac{N}{V_B})e^{a_2 T_f}\Delta x \quad \textbf{(2)}$$

K_{ad} is constant and depends on the tool and workpiece condition in the contact area. It can be considered that hardness follows an exponential behavior ($P_{weld}P_t = A_2 e^{a_2 \times T_f}$).

3 Materials and methods

Due to complicated tool movement, a CNC milling machine (CNC700MAHO) was used. A thread milling tool with a single edge (266 CoroThread) was used to fabricate threads on the grey cast iron workpiece. The aim of internal M30 fine threads (1.5 mm) required initial holes with a diameter of 27.5 mm. The hole length (the plate thickness) was considered as 24 mm. Fig. 3 shows images of the workpiece (Fig. 3-a), workpiece mounting on the machine table (Fig. 3-b), and the thread milling operation (Fig. 3-c). An optical microscope was used to capture images of the tool clearance plane and determination of flank wear.

(a) (b) (c)

Figure 3. (a) Grey cast iron workpiece (b) Workpiece clamping on the machine table (c) The thread milling operation.

The feed plan and cutting speed were considered as input parameters. According to preliminary experiments, cutting speed higher than 48 m/min led to a built-up edge (BUE). Hence, the cutting speed was adjusted between 26 and 48 m/min. Table 1 shows input parameters and related levels which were applied to experiments.

Table 1. Parameters and related levels.

Parameter	Level 1	Level 2	Level 3
Cutting speed (m/min)	*26*	*37*	*48*
Infeed plan	*Radial*	*Modified flank*	*Incremental*

ISO 3685 recommends the allowable tool flank wear (width of flank wear zone) of 0.3 mm. This way, in different cutting lengths, tool wear was measured. When flank wear reached 0.3 mm the machining was ended. In this regard and according to the helical tool path in the milling process, it was essential to calculate the cutting length. At first, the number of revolutions ($n_{revolution}$) should be evaluated through the following relation:

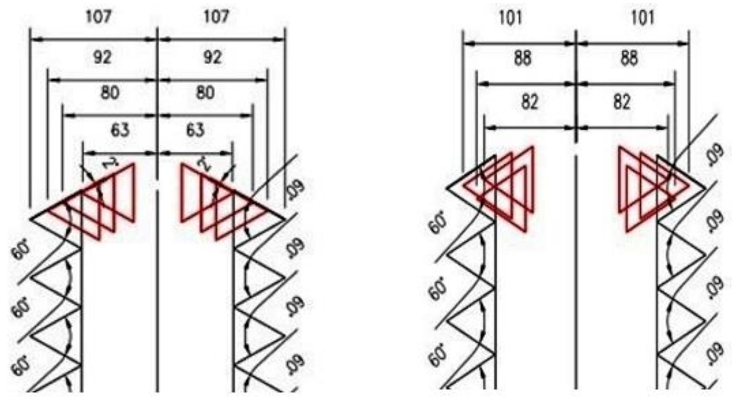
$$n_{revolution} = H \ / \ pitch = \frac{24}{1.5} = 16 \tag{1}$$

in which, H is the hole depth and thread pitch is chosen according to the thread fine profile (1.5mm). Employing the circumference of every revolution circle, the total cutting length ($L_{cutting}$) is equal to:

$$L_{cutting} = n_{revolution} \times \pi \times D \simeq 1386 \ mm \tag{2}$$

in which D is the tool revolution diameter.

Fig. 4-a & b show the tool path in the cases of modified flank and incremental plans. It should be noticed that the tool path for the two mentioned infeed strategies there are not exist in commercial software for generating the G-code of the tool path. So, the authors applied the G-code of the modified flank and incremental infeed strategies manually to the software (Fig. 4-c). This subject can be presented as a solution to improve the commercial software of tool path control.

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N1 G18 F360 S1700 T1 M67
N2 G52 M3
N55 G93 X121.7 Z-0.2
N3 G0 X0 Y2 Z2.8
N4 G1 Y0
N5 G91
N6 G2 Y -1.5 I0 K-2.8 B5=360
N7 G14 J 17 N1=6
N8 G90
N9 G1 Z0
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(a) (b) (c)

Figure 4. Tool path in (a) modified flank and (b) incremental plans (c) sample of G-code.

4 Results and Discussion

According to Section 3, tool flank wear originates from two mechanisms abrasion and adhesion. Both of them are affected by the temperature excessively. Hence, the first step to studying the variations of flank wear is analyzing the tool temperature behaviors in different threading strategies.

4.1 Temperature-FEM simulation

To predict the behavior of the flank wear and abrasion mechanism, a temperature study is a key method. In this way, the finite element method can be used to develop a numerical model to analyze temperature variations during different infeed plans.

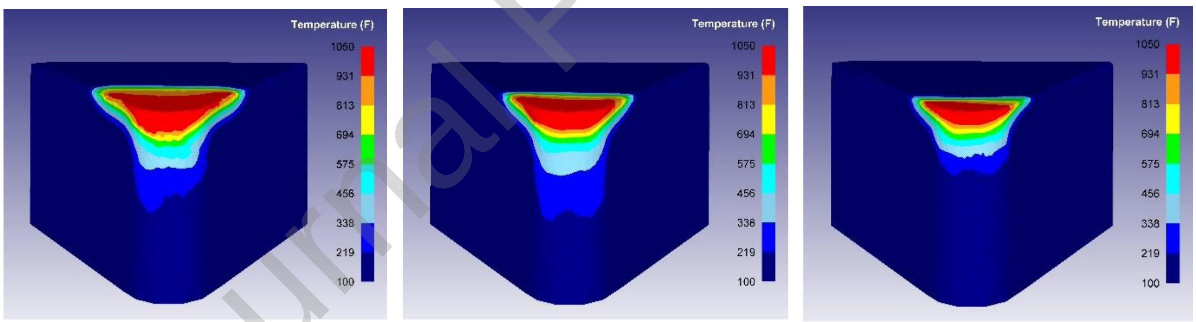
SFTC DEFORM as a commercial package was used to model the thread-cutting process. In this way, tool geometry and machining conditions were selected according to the experiments in which only the infeed plan was the variable parameter. The simulation type was Lagrangian Incremental and details of the FEM elements are presented in Table 2.

Table 2. Parameters and related levels.

	Element numbers	Element shape	Min element size (mm)	Max element size (mm)
Tool	*25000*	*Tetrahedral*	*0.100*	*0.201*
Workpiece	*30000*	*Tetrahedral*	*0.0254*	*0.509*

After performing the simulation in a transient condition, and after the required length is cut, machining is carried out in a steady-state condition. Hence, the results of temperature are shown in Fig. 5. According to Fig. 5, the mean temperature of the tool nose in radial, modified flank, and incremental infeed methods are 900°F, 850°F, and 780°F, respectively.

The radial infeed plan resulted in the highest temperature values which extend to the flank faces. Modified flank infeed found a smaller area of contact and lower friction was applied on the tool. Hence, a lower temperature was obtained (Fig. 5-b). Incremental infeed strategy includes the intermittent contact of each of the cutting edges to the workpiece. Hence, each of the cutting edges found a chance of cooling down. Finally, tool temperature was reduced compared to other plans which is presented in Fig. 5-c. Also, the consecutive images of flank wear progress using a radial infeed plan are shown in Fig. 6.



(a) (b) (c)

Figure 5. Results of temperature simulation during thread cutting (a) Radial (b) Modified flank (c) Incremental infeed plans.

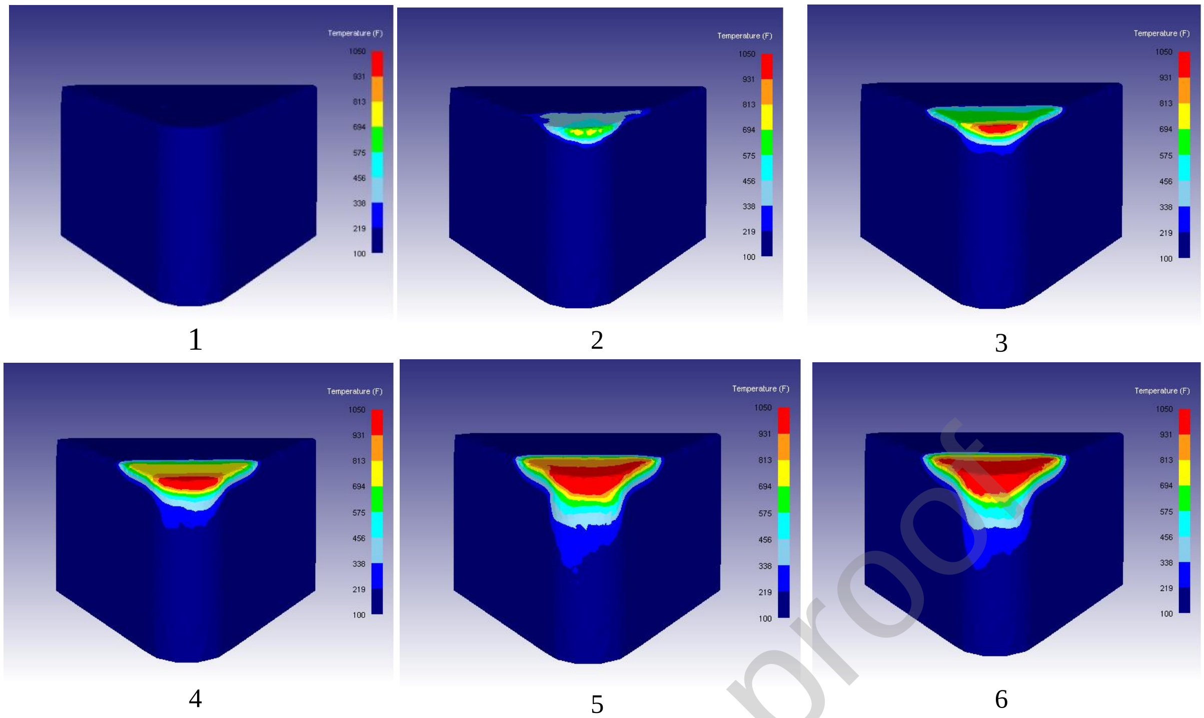


Figure 6. Consecutive images of wear progress using radial infeed plan.

4.2 Flank Wear-FEM simulation

To achieve a predictable model to analyze tool wear, a FEM simulation of the tool wear during the thread milling was developed using the SFTC DEFORM. This simulation was specified to the effect of infeed strategies on the tool wear so three states of the model were employed. According to Fig. 7-a, to study the flank wear, two flank faces should be considered and compared to experimental results. This way, two views of A and B were determined, and the worn zone was captured. Microscopic images proved the accuracy of the thread milling FEM simulations (Fig. 7-b). All machining characteristics were considered the same and only infeed mechanisms were variable. As can be seen, the same as experimental results, simulations proved that the incremental infeed strategy presented the minimum tool wear followed by the modified flank infeed. Radial infeed presented the maximum flank wear values.

A comparison of simulation and experimental results in both views of A and b shows the acceptable agreement between results and proved the validity of the developed FEM model.

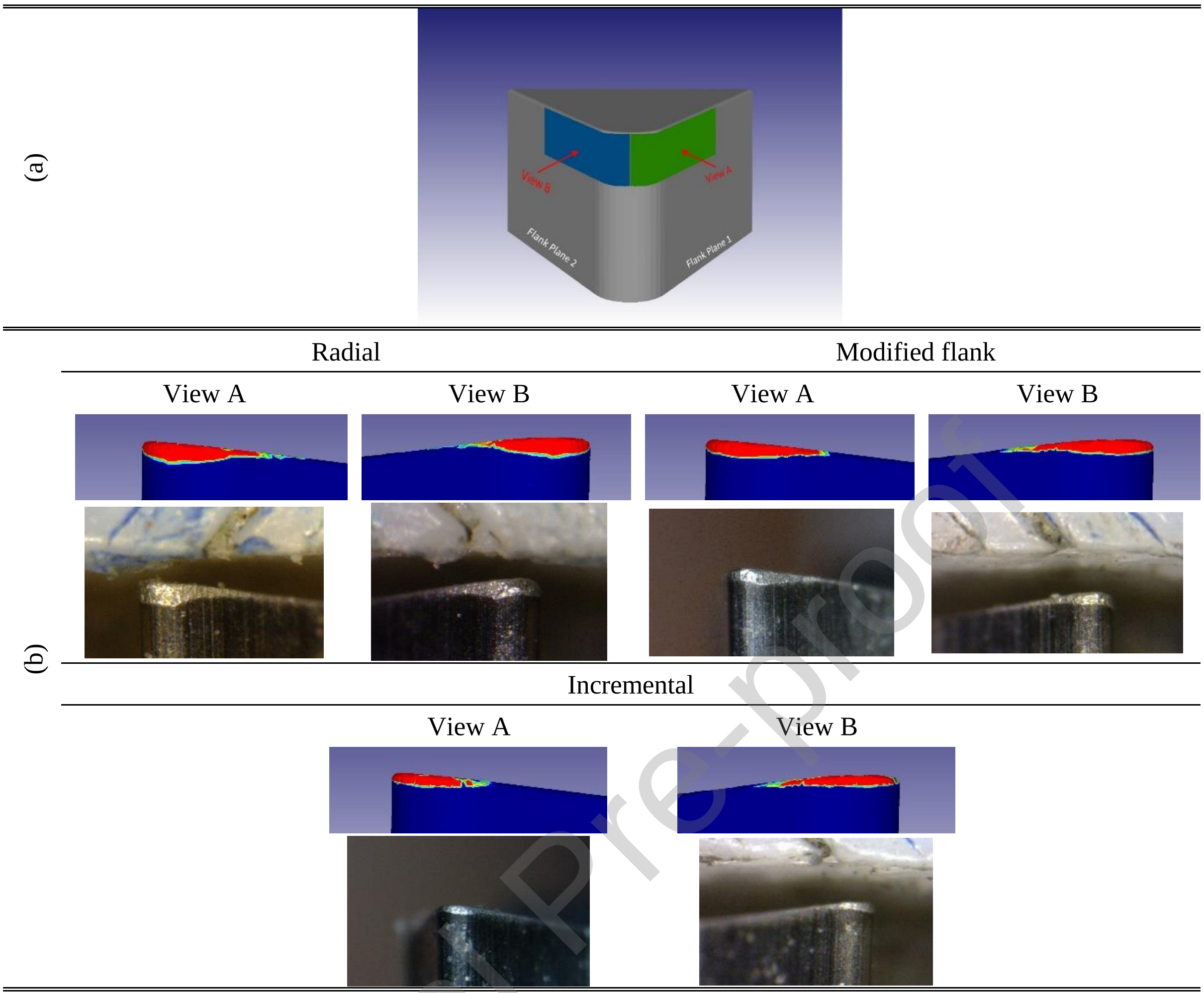


Figure 7. (a) Tool characteristics to present results of flank wear (b) Experimental and numerical results of wear during thread cutting on two main flank planes.

4.3 Flank Wear-experimental

4.3.1 Effect of infeed strategy

Fig. 8 shows the microscopic images and experimental results of the tool life (cutting length) using the cutting speed of 26 m/min according to three different infeed strategies. As can be seen, worn areas are extended on the flank faces and find maximum values close to the tooltip. Hence, in an area close to the tooltip, the width of the worn area was measured and considered as flank wear.

According to Fig. 8, the tool with radial infeed strategy reached the critical flank wear value after 1000 cm of the machining length. On the other hand, the modified flank plan reached critical tool flank wear after 1250 cm of cutting length. On the other hand, incremental infeed reached the allowable flank wear after cutting of 2800 cm which presents a significant cutting length improvement.

Regarding sections 3 and 5.1, during the modified flank and incremental infeed mechanism, the tool experiences lower mean temperature compared to the radial strategy. Hence, the main mechanisms of abrasion and adhesion are neutralized and more tool life and cutting length are expected. Between modified flank and incremental strategies, incremental presented much higher machining length which originated from consecutive edge replacement during incremental infeed. Indeed, by edge replacement, the tool finds enough time to cool and machining load divided between two edges compared to one edge of the modified flank strategy. Hence, the tool mean temperature is reduced and higher tool life is achieved.

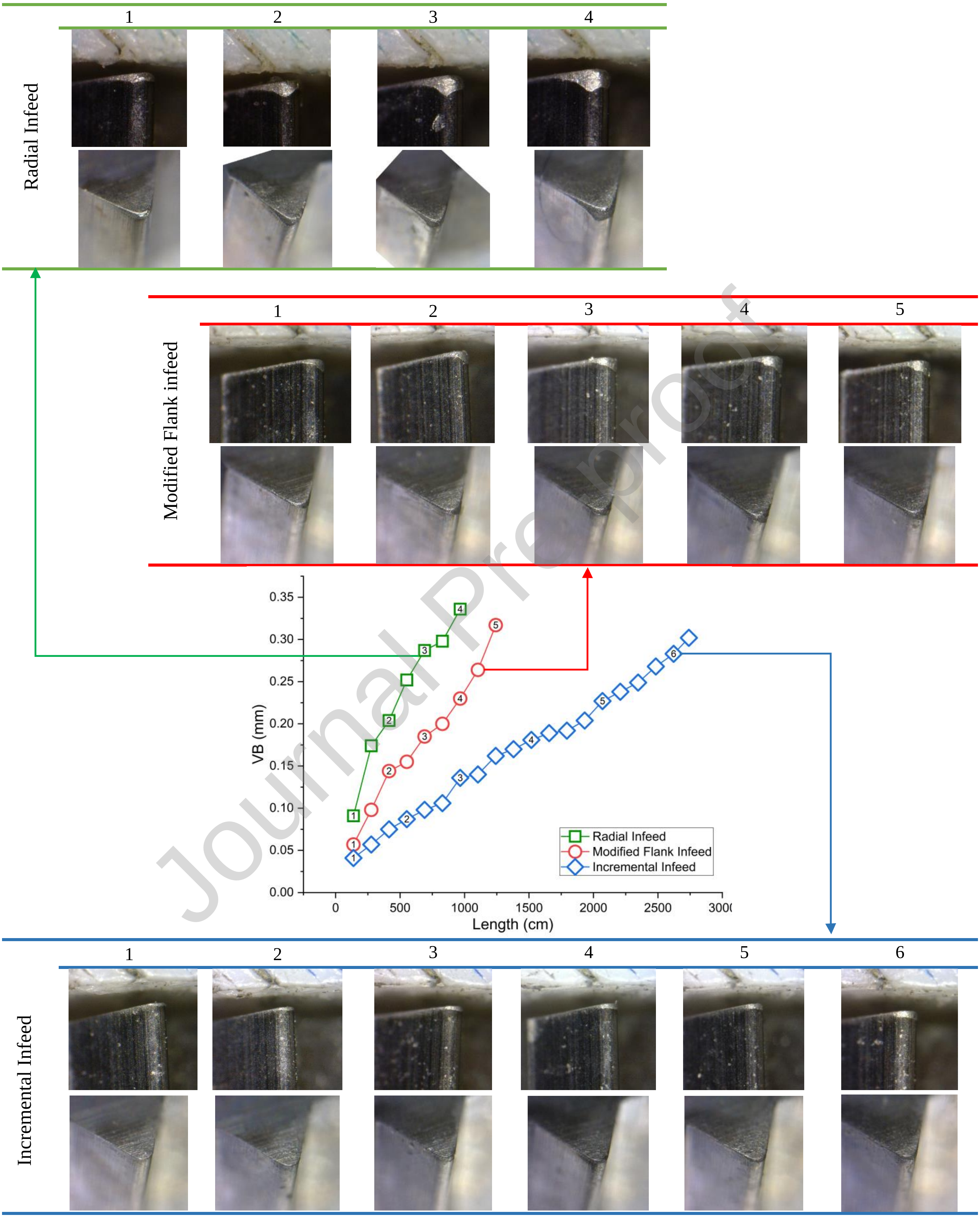


Figure 8. Images and numerical results tool flank wear in cutting speed of 26 m/min.

Temperature rise affects the hardness of the tool more than hardened particles. In this way, P_t reduces significantly, and consequently based on Eq. (1), dV_{ab} increases and higher flank wear is expected. As a result, any variation in the machining process which leads to the higher tool temperature can reduce the tool life through the formation of great flank wear.

Also, adhesive wear dV_{ad}, according to Eq. (2), increases by rising tool temperature exponentially. In the incremental infeed method, not only does reducing the engagement of the edge of the tool and the workpiece reduce the wear of the tool but other wear mechanisms such as adhesion are also reduced and it doubles down the tool wear.

4.3.2 Effect of cutting speed

The practical cutting speed is important because it is too desirable that apply the maximum cutting speed to achieve the highest production rate simultaneously and keep tool life without significant reduction. Hence, the effects of cutting speed on the improvement of three infeed mechanisms are presented in Fig. 9. According to improvement percentages, two main changes can be emphasized with some delay. The incremental infeed method presents a great improvement of 228% in cutting speed of 37 m/min compared to the radial method. It means that in this speed, radial infeed led to great tool flank wear while the incremental strategy did not change significantly so a huge tool life (cutting length) was achieved. The same trend can be observed for the incremental infeed method in comparison to the radial method in cutting speed of 48 m/min with an improvement of 340%. As known in machining mechanics, increasing the cutting speed leads to higher tool temperature and results in smaller tool life. But during the two infeed methods, tool temperature rise is lower compared to radial strategy so higher speed can be applied and more production rate can be available while tool flank wear does not change excessively.

From an abrasion viewpoint: By increasing the cutting speed, the chip receives more thermal energy. Therefore, the temperature of the shear zone and the temperature of the chip-tool contact increase, and consequently there is expected to be a decrease in the shear flow stress in the shear zone and the chip-tool friction area. As a result, the cutting forces were reduced by an increase in cutting speed. Also, at higher cutting speeds, the heat transfer limits and the temperature of the tool flank face increases. The higher temperature reduces the hardness of the tool and leads to more tool flank wear. Therefore, in the abrasion mechanism of flank wear, two opposing factors affect wear. By increasing the cutting speed, lower cutting forces reduce tool wear while higher tool temperature signifies the tool wear.

From an adhesion viewpoint: According to the adhesion mechanism, adhesion values increase exponentially by increasing the cutting speed and the temperature of the tool-chip contact. Hence, each machining variable which increases the temperature, signifies both parameters of adhesion mechanism of flank wear.

Totally, in higher values of the cutting speed in which large wear is expected, temperature is the main effective variable. Along with temperature rise, adhesion wear plays a more important role compared to other mechanisms because the neutralizing parameter of cutting forces has no noticeable effect on the adhesion. It should be noticed that the temperature rise mainly originated from the friction on the tool-chip contact area. Hence, each infeed strategy that applies a small contact area limits the source of friction, and consequently by increasing the cutting speed, the temperature rise gradient limits and finds small values. As a result, tool life does not change, significantly by the application of high speeds. This behavior can be observed in the comparison of three main infeed mechanisms and improvement percentages of modified flank and incremental strategies compared to radial infeed (Fig. 9). According to Fig. 9 can be observed that:

1- Radial infeed has the highest contact length so the largest temperature rise gradient is expected and tool life is rapidly reduced.

2- The modified flank strategy engaged only one edge so the contact length is smaller compared to the radial infeed and better tool life presented. In cutting speed of 48 m/min, a significant difference of 80% proves the effect of temperature variation gradient.

3- Incremental infeed employs one edge and consequently replaces them. Hence, it finds the lowest temperature rise gradient which is obvious by attention to cutting length of 2800 cm in cutting speed of 26 m/min. On the other hand, because of the lower mean temperature, a huge improvement of 228% and 340% was achieved in cutting speeds of 37 m/min and 48 m/min, respectively.

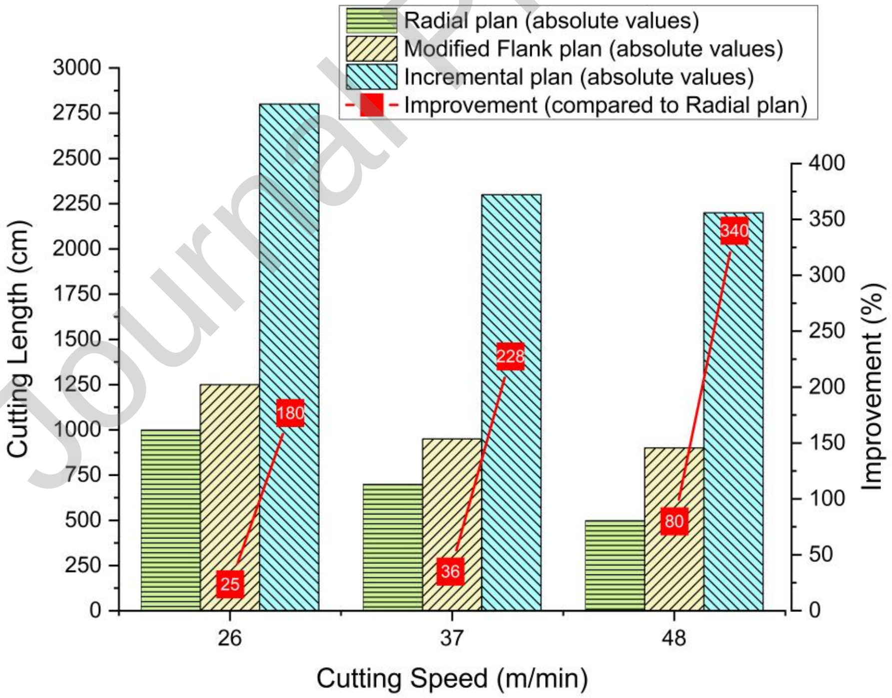


Figure 9. Cutting length variation in different infeed plans and improvement percentages compared to the radial plan (arrows show the speed of significant improvement percentages).

4.4 Thread surface quality-experimental

Wear mechanisms act on the cutting tool and change its geometry. On the other hand, these mechanisms act on the thread surface and may affect the surface accuracy and quality. By continuing the thread cutting, wear on the tool flank face is extended and the tool-workpiece contact area is growing. In this way, more friction force is generated and higher temperature facilitates the abrasion and adhesion mechanisms which finally produce an inaccurate thread surface. According to Fig. 10, for every infeed strategy, tool wear, and fabricated thread surfaces are presented. In radial infeed, more tool wear and consequently lower quality surface thread can be observed. Variation of the infeed strategy to modified flank and incremental leads to smaller flank wear with more quality and accuracy of the thread geometry.

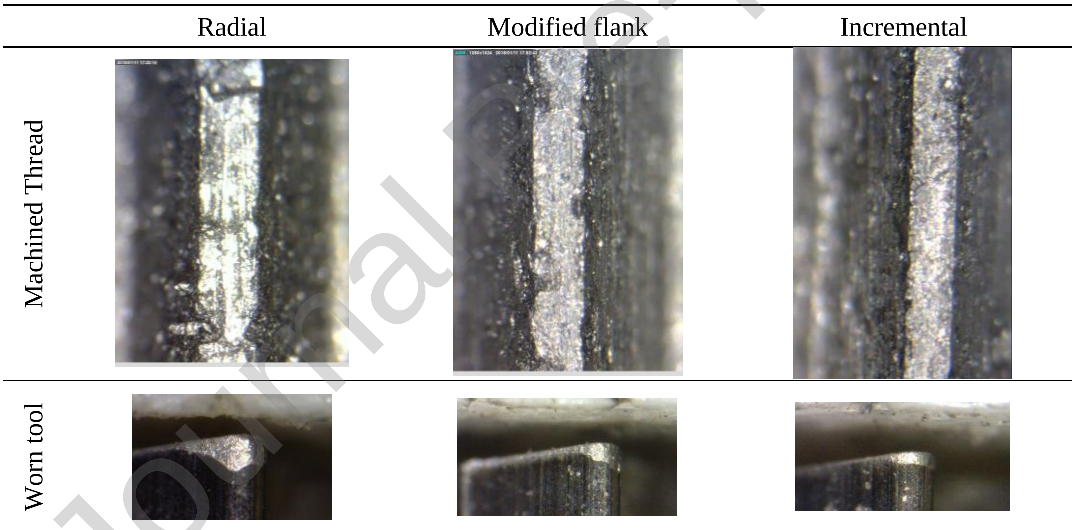


Figure 10. Fabricated thread profile after thread milling with different infeed plans versus related worn tools.

5 Conclusions

Current research focuses on the effects of infeed strategies and cutting speed on the tool flank wear during the thread milling process. Results can be classified as follows:

1- Results of FEM simulation of the tool temperature showed that incremental infeed reached the minimum tool temperature while the common radial infeed provide the highest tool temperature.
2- To predict tool wear during thread milling, a FEM model was developed. Comparison of numerical results to microscopic images showed the acceptable agreement between obtained results and proved the validity of the employed FEM model.
3- There is not the same proportion between increasing the machining characteristics and tool wear. The contribution of every wear mechanism differs by temperature rise (increasing the cutting speed). Hence, increasing the cutting speed twice did not result in twice tool wear. This point can be applied to optimize machining time and cost.
4- In a cutting speed of 26 m/min, radial infeed provided a cutting length of 1000 cm while modified flank and incremental infeed strategies presented cutting lengths of 1250 and 2800 cm, respectively. A comparison of cutting length (tool life) showed that incremental infeed can present a great improvement of 340% of tool life compared to radial infeed. On the other hand, modified flank infeed at a higher cutting speed of 48 m/min reached a cutting length improvement of 80% compared to radial infeed.
5- Incremental and modified flank strategies employed small tool-chip contact areas which resulted in lower tool temperature and higher tool life (cutting length). Also, incremental infeed replaced cutting edge, intermittently. Hence, it distributed wear on two edges which finally led to the highest tool life (cutting length) between all infeed strategies.

Industrial recommendation for commercial software

Infeed strategy has a great effect on the properties of the threading process, but commercial software which is widely used, does not include the related G-code of the mentioned strategies.

Authors recommend adding paths and related G-codes of infeed strategies to make commercial software more suitable for the threading process.

Disclosure statement

The authors declare no conflict of interest.

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Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Highlights

- *Study of the tool flank wear during the thread milling process using experimental procedure and numerical simulation.*
- *Study the effect of infeed strategies (radial, modified flank, and incremental) on flank wear.*
- *Study the effectiveness behavior of infeed strategies on the flank wear in different cutting speeds.*
- *Study the wear mechanisms in different infeed strategies with special attention to the tool temperature.*
- *FEM simulation of the tool temperature.*
- *FEM simulation of the tool wear; validation according to experimental results of flank wear.*
- *Compare threads' surface quality according to three infeed strategies.*