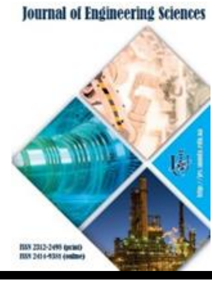
JOURNAL OF ENGINEERING SCIENCES

Volume 8, Issue 2 (2021)

Panchuk V., Onysko O., Kotwica K., Barz C., Borushchak L. (2021). Prediction of the accuracy of the tapered thread profile. Journal of Engineering Sciences, Vol. 8(2), pp. B1-B6, doi: 10.21272/jes.2021.8(2).b1



Prediction of the Accuracy of the Tapered Thread Profile

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Article info:
Submitted: July 29, 2021
Accepted for publication: November 4, 2021
Available online: November 9, 2021

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Abstract. The efficiency of drill string largely depends on the pipe-end connector's accuracy named tapered thread tool joint. Most of those are made by using lathes. Turning tools were made with a profile identical to the thread profile, and all well-known world brands' plants make the back rake angle of such a cutter with zero value. This is obviously due to the lack of a precise algorithm for calculating the cutter profile and ensuring the accuracy of the tapered thread profile. A virtual experiment was carried out of three-dimensional modeling of the process for shape creation. It showed that in the case of lathe machining of the thread of NC23 type, the deviation from the nominal half profile of the obtained thread is only 0.02°. This result prompted the decision to propose a new algorithm for predictive calculation of the half-angle of the cut profile based on the parameter associated with actual turning – the working height of the profile – h in contrast to previous scientific sources where this calculation was based on the parameter H – not truncated thread Height which is associated with the theoretical base of the accuracy of the thread. The result of the program application, created based on the algorithm proposed in the article, showed that the predicted accuracy of the obtained profile's half-angle could be in a range from –0.03° to +0.10°, which is equivalent to 4–13 % of tolerance of this dimension.

Keywords: flank, not truncated thread Height, back rake angle, half profile angle, angle of inclination.

1 Introduction

Tapered threads are very widely used to connect drill pipes. These threads are made using lathe cutters, the profile of which is equivalent to the profile of the thread itself. However, companies that manufacture these tools adhere to only one value of the leading angle – zero. This is because the theoretical basis has not yet become known, and there is no appropriate algorithm for calculating the profile of the tool's cutting edge with a non-zero value of the leading angle.

There are a number of publications that, to some extent, represent the study of high-strength and high-precision tool-joint tapered threads. In paper [1], the connection test was carried out on the threaded joint. According to the test data and the simulation results, the final joint thread structure was optimized, which is fundamental in designing a tool joint. But only the stress distribution in the joint thread was indirectly studied. However, the accuracy of the thread was not investigated.

This model is a proper benchmark for assessing the quality of a joint thread seal is presented in [2]. But only the analysis software ANSYS Workbench is applied to stimulate the distribution of contact stress and sealing properties. The accuracy of the manufactured thread was not researched in it.

In the study [3], the implemented data acquisition system allowed us to know, in real-time, the intensity of the cutting force in conventional lathes. But these researchers did not deal with the machining of thread

The cutting tool profile depends on the operating parameters and the required geometry, using a numerical model based on an analytical model based on a tangential motion condition [4]. But this research is about whirling but not threading machining.

2 Literature Review

An impact of the edge and the rake angle of the lathe tool on the strength field was studied experimentally in the paper [5]. In research [6] using the cutting force prediction and using a validated mechanistic force model, the energy consumption in turning can be estimated. The accuracy of manufactured thread is not researched in [5,6].

The study [7] focuses on the threading of non-symmetric profiles. But that method of machining is milling only. The only stress concentration factors in the pin and box are calculated in [7].

In the study [8], the NC35 tool joint with the double shoulder is considered the research object and studied by finite element method (FEM) using nonlinear thermo-mechanical coupled-mode but not using the accuracy parameters of thread. In [9], the generalized mechanics model of multi-point thread turning operations is presented. The model can be used for both turning planning but not for accurate prediction.

The paper [10] deals with the comparison of measured and calculated results of cutting force components. The paper [11] studies the dependence of the dynamic oscillatory movements in the area of drill string sticking on the parameters of the vibrating mechanism only.

In [12], the authors developed a laser triangulation device to measure deformations but not the accuracy of thread joint details. The article [13] deals with studying the vector components of the kinematics of the surface forming of the tapered thread by turning machining and does not study the influence of tool profile on thread accuracy.

The effect of the accuracy of the profile pin threads for equivalent stresses, fatigue safety indicators, and contact pressure in drill pipe joints are studied in paper [14].

So the purpose of this research is: learn the counter algorithm of the influence of the geometric parameters of the tool on the profile deviations of the tapered thread made by the lathe.

3 Research Methodology

3.1 Calculation of the profile angle based on the theoretical parameter *H*

The algorithm for calculating the profile of the tool-joint tapered thread based on the developed theoretical basis is presented in [15]. Theoretically, it is based on the parameter H – not truncated thread Height (Figure 1).

According to this scheme, the angles are calculated by formulas [15]:

$$\alpha_{AD} = arctg\left(\frac{|Z_a - Z_d|}{|X_a - X_d|}\right); \tag{1}$$

$$\alpha_{AB} = arctg\left(\frac{|Z_a - Z_b|}{|X_a - X_b|}\right); \tag{2}$$

$$Z(x) = tg\,(\alpha_1)x\frac{sin\tau}{sin\gamma} - \frac{P\tau}{2\pi}; \tag{3}$$

$$\tau = \gamma - \arcsin\left(\frac{d_{minor}}{2x}sin\,\gamma\right), \tag{4}$$

where α_1 –the angle of the profile of the cutting edge of the cutter, for a conventional cutter $\alpha_1 = 30°$; P – the thread pitch, d_{minor} – the inner diameter of the thread (Figure 2).

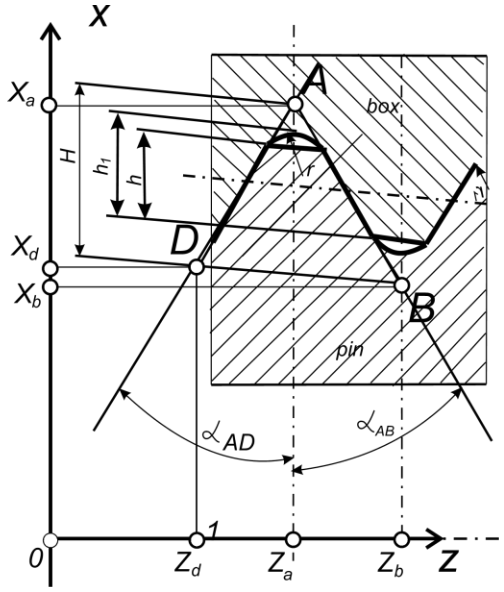

Figure 1 –Scheme used for calculating the half angles of the profile of a tool-joint tapered thread based on the parameter *H*

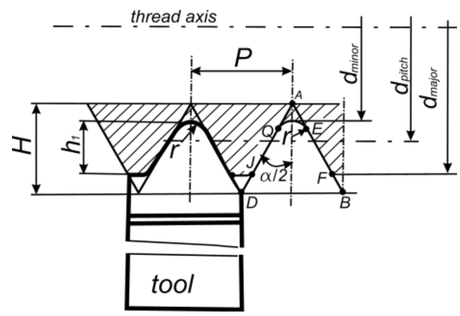

Figure 2 – The scheme of the half angles of the thread profile based on the parameter *h*

However, the parameter H is theoretical, and the parameters h and h1 are effective in the real tool-joint tapered thread. The parameter h_1 is the one that is realized with the help of a cutting tool, and the parameter h – the working height of the thread is actually decisive for the straight section of such an implementation. In Figure 2, the profile of the cutter is shown by a bold line, and the obtained straight sections of the profile are marked between the points J and Q and between the points E and F. Half profile angle – $\alpha/2$ is the angle between the straight side section and the axis of symmetry of the threaded turn. The radius of the obtained radial part is r. However, the algorithm represented by equations (1) and (2), based on the scheme in Figure 1, determines the half profile angles of the sides of the original triangle *ADB* using the coordinates of the points: X_a, X_d, X_b and calculated by formulas (3), (4) and is corresponding to their coordinates Z_a, Z_b, Z_d.

3.2 Calculation of the profile angle based on the actual parameter *h*

According to the API 7 standard, one of the parameters of a tool-joint tapered thread is the value of b – root truncation (Figure 3). Using this parameter, you can represent the following relationship:

$$H = b + h + b. \qquad (5)$$

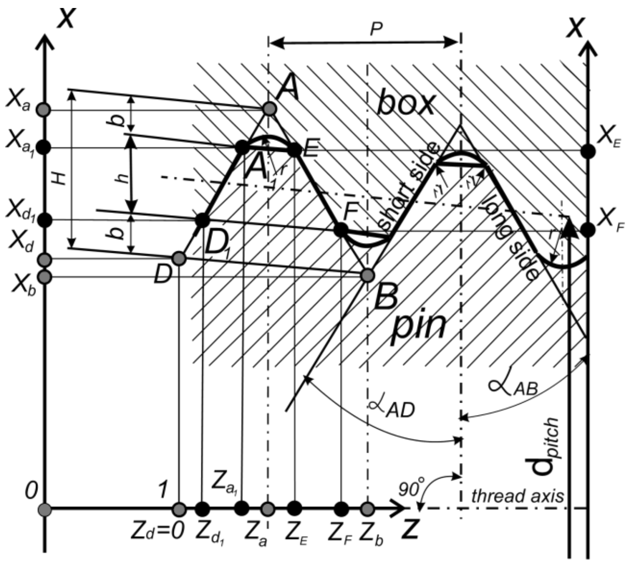

Figure 3 – Scheme used for calculating the half angles of the profile of a tool-joint tapered thread based on the parameter *h*

Thus, by analogy with equations (1)–(2), we can present the calculation of the half profile angles of the tool-joint tapered thread in its shaping by a real cutter based on Figures 2–3:

$$\alpha_{A_1D_1} = arctg\left(\frac{|Z_{a_1} - Z_{d_1}|}{|X_{a_1} - X_{d_1}|}\right); \qquad (6)$$

$$\alpha_{EF} = arctg\left(\frac{|Z_F - Z_E|}{|X_F - X_E|}\right), \qquad (7)$$

where the coordinates X_{a1}, X_{d1}, X_F, X_E can be determined by the formulas:

$$X_{a_1} = X_a - b; \qquad (8)$$

$$X_{d_1} = X_d + b; \qquad (9)$$

$$X_F = X_b + b; \qquad (10)$$

$$X_E = X_d - b. \qquad (11)$$

The coordinates Z_{a1}, Z_{d1}, Z_F, and Z_E can be determined by formulas (3) and (4).

Figure 4 of [15] can serve as an illustration of the difference between the algorithm based on equations (1)–(2) and the algorithm based on formulas (6)–(7). It shows a red straight line according to the API 7 standard, and a blue curve shows the profile predicted by turning the profile. The Z coordinate of the last point of the blue profile is visibly different from the Z_1 coordinate of the red profile. However, the values of the *z*-coordinates corresponding to the points with X coordinates between 34.0 mm and 35.75 mm are not so obvious.

Given that the value of b = 1.43 mm, the initial value of X = 32.6, and the final X = 37.1, we can determine the following: the real range of coordinates X according to formulas (8)–(11) between 32.60 + 1.43 = 34.03 (mm) and 37.10–1.43 = 35.58 (mm).

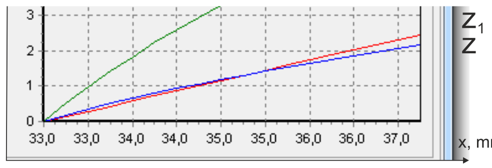

Figure 4 – Diagrams of rectilinear sections of profiles given by the standard thread (red line) and made by a cutter with a non-zero value of the back rake angle

4 Results

4.1 Predicting of the accuracy of the profile obtained by the simulated turning of the thread of size NC23

In order to verify the algorithm declared above, a model of forming a tapered thread of size of NC23 by lathe is submit on Figure 5.

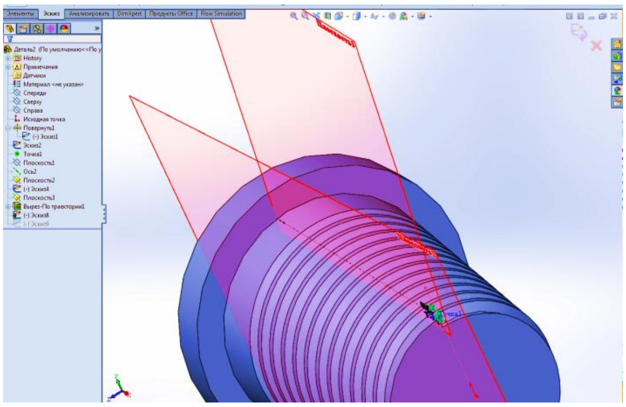

Figure 5 – Model of shaping of tool-joint tapered thread of NC23: 2 – plane, normal to the tangent to the first turn of the thread (λ = 2.61°); 3 – plane of the rake surface of the tool with negative back rake angle γ = –5°

The geometric parameters of the tool are selected: the back rake angle γ = –5°, and the angle of inclination λ = 2.61°, which corresponds to the slope of the first turn of the thread.

The axial section of the shape-created model of the specified size shows the high accuracy of a thread profile in the axial plane – 60.02° (Figure 6).

The API 7 standard provides for the accuracy of the half-angle of the profile of the notch $\alpha/2$ = 30° ± 0.40'. Thus, the high accuracy of the cut profile of the thread provided on the 3D model proves the need of the creation on the basis of equations (3)–(11) of a special automatic algorithm for calculating the profile of the thread and the implementation of its analysis of its predicted accuracy.

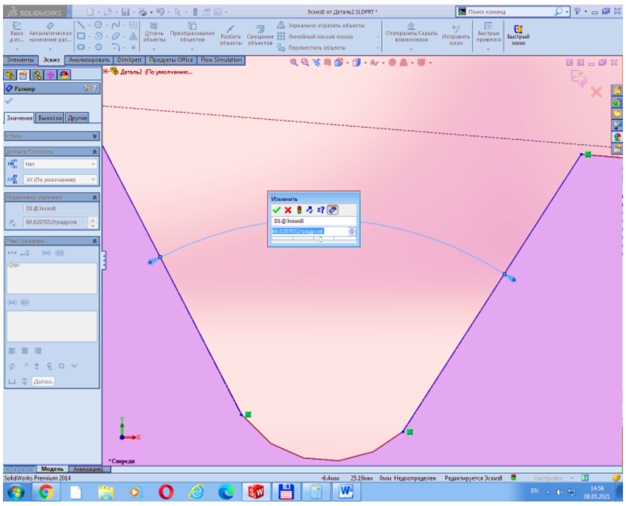

Figure 6 –Prediction of the axial profile
on the threaded model NC23

4.2 Software prediction of the accuracy of the profile of the tapered thread NC23 made by lathe

Software implementation of the algorithm for calculating equations (3) and (4) provides for the input parameters: the size of the thread, the back rake angle of the cutter, the angle of inclination of the thread, the step of calculating the X coordinate, as well as selecting the desired distance from the pin end to this turn, long or the small side (A_1D_1) of the *EF*.

Figure 7 shows a fragment of the program where the back rake angle is –5°, the inclination angle for the turn at a distance of 60.125 mm – 1.8 ° (Corresponds to the latter in the direction from the end of the turn). The calculating step is 0.1 mm.

Figures 8–10 show fragments of the forecast calculation starting from point D ($X = 27.16$, $Z = 0$), and ending with point A ($X = 32.66$, $Z = 3.18$).

The coordinate Z_1 in the program refers to the profile of the cutter in case of need for its modernization, the coordinate. Coordinate Z_2 is the predicted axial profile according to formulas (3)–(4), obtained by a tool with the specified geometric parameters ($\gamma = –5°$, $\lambda = 1.8°$), and the profile of the cutting edge, which is identical to the nominal profile of the standard thread ($\alpha/2 = 30°$).

Given that the standard API 7, $b = 1.43$ mm (root truncation) and using formula (9), we obtain $x_{d1} = 28.59$ mm, which is closest to the value of 28.56 mm in the program fragment in Figure 9, which means the corresponding value of the coordinate $Z_2 = 0.815$ mm.

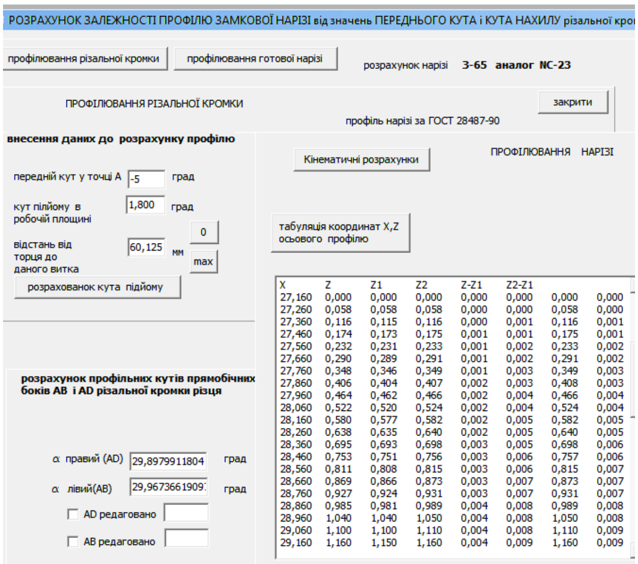

Figure 7 – Visual application for predictive calculation of the profile of the thread NC23

X	Z	Z1	Z2
27,160	0,000	0,000	0,000
27,260	0,058	0,058	0,058
27,360	0,116	0,115	0,116
27,460	0,174	0,173	0,175
27,560	0,232	0,231	0,233
27,660	0,290	0,289	0,291
27,760	0,348	0,346	0,349
27,860	0,406	0,404	0,407
27,960	0,464	0,462	0,466
28,060	0,522	0,520	0,524
28,160	0,580	0,577	0,582
28,260	0,638	0,635	0,640
28,360	0,695	0,693	0,698
28,460	0,753	0,751	0,756
28,560	0,811	0,808	0,815
28,660	0,869	0,866	0,873
28,760	0,927	0,924	0,931
28,860	0,985	0,981	0,989
28,960	1,040	1,040	1,050
29,060	1,100	1,100	1,110
29,160	1,160	1,150	1,160

Figure 8 – Projected thread profile NC23
short side *AD* last turn (part 1)

Given that the API 7 standard, $b = 1.43$ mm (root truncation) and using formula (8), we obtain $x_{a1} = 31.23$ mm, which is closest to the value of 31.26 mm in the program fragment in Figure 10. Therefore, the corresponding value of the coordinate $Z_2 = 2.38$ mm.

29,060	1,100	1,100	1,110
29,160	1,160	1,150	1,160
29,260	1,220	1,210	1,220
29,360	1,270	1,270	1,280
29,460	1,330	1,330	1,340
29,560	1,390	1,390	1,400
29,660	1,450	1,440	1,450
29,760	1,510	1,500	1,510
29,860	1,560	1,560	1,570
29,960	1,620	1,620	1,630
30,060	1,680	1,670	1,690
30,160	1,740	1,730	1,740
30,260	1,800	1,790	1,800
30,360	1,850	1,850	1,860
30,460	1,910	1,910	1,920
30,560	1,970	1,960	1,980
30,660	2,030	2,020	2,040
30,760	2,080	2,080	2,090
30,860	2,140	2,140	2,150
30,960	2,200	2,190	2,210
31,060	2,260	2,250	2,270
31,160	2,320	2,310	2,330

Figure 9 – Projected thread profile NC23
short side *AD* last turn (part 2)

30,660	2,030	2,020	2,040
30,760	2,080	2,080	2,090
30,860	2,140	2,140	2,150
30,960	2,200	2,190	2,210
31,060	2,260	2,250	2,270
31,160	2,320	2,310	2,330
31,260	2,370	2,370	2,380
31,360	2,430	2,420	2,440
31,460	2,490	2,480	2,500
31,560	2,550	2,540	2,560
31,660	2,610	2,600	2,620
31,760	2,660	2,660	2,670
31,860	2,720	2,710	2,730
31,960	2,780	2,770	2,790
32,060	2,840	2,830	2,850
32,160	2,890	2,890	2,910
32,260	2,950	2,940	2,960
32,360	3,010	3,000	3,020
32,460	3,070	3,060	3,080
32,560	3,130	3,120	3,140
32,660	3,180	3,180	3,200

Figure10 – Projected thread profile NC23
short side *AD* last turn (part 3)

The obtained results are entered in Table 1 (right column) and on their basis and using formulas (1) and (6) the forecast calculations α_{AD} = 30.19°, and α_{A1D1} = 30.10° are obtained (highlighted in bold in the right column of Table 1).

Table 1 – Data for counting profile angle of short flank *AD*

Parameters	The 1st turn (λ = 2.61°)	The last turn, (λ = 1.8°)
X_a	22.16 mm	27.16 mm
Z_a	0.00 mm	0.00 mm
X_d	27.66 mm	32.66 mm
Z_d	3.20 mm	3.20 mm
α_{AD}	30.19°	30.19°
Xa_1	23.59 mm	28.59 mm
$Xa_{1\ table}$	23.56 mm	28.56 mm
Za_1	0.815 mm	0.815 mm
Xd_1	26.23 mm	31.23 mm
$Xd_{1\ table}$	26.26 mm	31.26 mm
Zd_1	3.18 mm	2.38 mm
α_{A1D1}	30.09°	30.10°

Similar calculations were performed for the first thread turn of the pin, for which λ = 2.61°. The prediction of the half profile angle with respect to the long side was performed according to formulas (2) and (7) and using formulas (10) and (11), and these results are presented in Table 2.

Table 2 –Data for counting profile angle of long flank *AB*

Parameters	First turn(λ=2.61°)	Last turn (λ==1,8°)
X_a	22.16 mm	27.16 mm
Z_a	0.00 mm	0.00 mm
X_b	27.96 mm	32.96 mm
Z_b	3.34 mm	3.34 mm
α_{AB}	29.94°	29.94°
X_E	23.59 mm	28.59 mm
$X_{E\ table}$	23.56 mm	28.56 mm
Z_E	0.805 mm	0.807 mm
X_F	26.53 mm	31.53 mm
$X_{F\ table}$	26.56 mm	31.56 mm
Z_F	2.53 mm	2.54 mm
α_{EF}	29.90°	29.97°

The data in Tables 1–2, which are highlighted in bold, indicate the values of the half profile angles $\boldsymbol{\alpha_{AD}}$ and $\boldsymbol{\alpha_{AB}}$, which are programmatically predicted based on the theoretical parameter *H* by formulas (1) and (2) (at the top) and α_{A1D1} and α_{EF} by equations (6) and (7) based on the actual parameter h in the lower part. Three of the four values of the half-angle based on the actual parameter *h* are ones with a minor deviation from the nominal value of 30° than the value of the half-angle according to the theoretical parameter *H*

5 Conclusions

The presented forecast calculations give good reasons to consider the equation based on the actual parameter *h* (working height of the thread). Therefore, the predicted accuracy of lathe machining the thread by the parameter of the half-angle of the profile can reach the initial value in a range from –0.03° to +0.10°. This range is equivalent to 4–13 % of the tolerance on the half-angle α – 45'.

The three-dimensional model reveals a more accurate execution of the thread profile (0.02°), but the software implementation allows visual-graphical profiling and analytical with any step of calculation accuracy.

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