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Modelling of the Effect of Different Infeed Angles and Cutting Areas on the Cutting Forces in External Threading

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Abstract

Variations in cutting forces were investigated experimentally depending on infeed angles and cutting areas in the external threading on a CNC turning centre. For this purpose, AISI 1050 workpiece material, 16ERM AG 60 IC 908 cutting tool, and SER 2525 M16 tool holder were used. External threading operations were performed using 0°, 14.5°, 15°, 27.5°, and 30° infeed angles while the cutting speed was held constant at 100 m/min for the experiments. Experimental results showed that the infeed angle and cutting area had significant effects on the main cutting force and the radial force components were considerable in threading operations in terms of energy consumption. In addition, the optimum infeed angle was 30° in the external threading operations in terms of cutting forces.

Key words: External threading, Infeed angles, Cutting forces

Introduction

Threading a workpiece is a fundamental manufacturing process. Threads can be produced using 2 basic processes, cutting and plastic deformation or forming. Threads produced by plastic deformation are stronger because of the grain structure than those produced by cutting, although forming cannot achieve the high accuracy and precision required in many applications. Threads made of brittle materials also cannot be produced by plastic deformation. In addition, external threads can be cut with a die and internal threads can be cut with a tap. However, for some diameters, no die or tap is available. In these cases, threads can be cut on a lathe. Threads may be cut using either a single or multi-point cutting operation. In contrast to the more traditional processes, the threads are formed using a single-point tool in a lathe (Amstead et al., 1987; Smith, 1989; Badami et al., 2003; Araujo, 2004).

In single point turning operations, for example threading, each side of the cutting tool forms chips synchronously. In that case the chip shaped by the cutting sides resists more and specific cutting force becomes higher compared to orthogonal cutting. Chips collide with each other while flowing in different directions and this affects the forces affecting the cutting area or chip surface. This event is called "chipping". Suzuki et al. analysed cutting forces to investigate chip collide using a straight tool cutting with 3 sides. Theoretical results showed that colliding of chips occurs when the specific cutting forces increase (Suzuki, 1993). During threading, there are various kinds of fluctuations and these fluctuations are always accompanied by non-linearity. These affect some formations in the cutting tool depending on tool geometries and cutting parameters. These formations in the cutting tool generally come to an end by chipping, wearing, and the end of the tool life. For this aim the cutting forces on the cutting tool should be considered when selecting the cutting parameters. Undesirable cutting forces result in more energy consumption and reduction in tool life (Black, 1996; Gunay, 2004). In threading operations, the increase in the main cutting force depends on friction between the cutting tool and the workpiece. That is to say, the cutting tool creates the thread with both sides (main cutting edge and trailing edge) and it causes an increase in friction between the cutting tool and the workpiece and thus an increase in cutting forces (Abdel, 1981). Generally, the increase in the cutting forces causes the V-shaped type of flank wear on the cutting tool (Ezugwu, 1999). In addition, the V-shape type of flank wear, concentrated along the tool nose, alteration in edge geometry, loss of compressive strength, and thermal cracking occur during threading (Ezugwu and Okeke, 2001).

Over the last few decades, some possible approaches for improving productivity during threading have been suggested by researchers but solutions to the problems in threading are relatively scarce. One of these solutions is altering the infeed angle. Many infeed angles can be used in threading but many of the CNC operators are not aware of the effects of infeed angles on the threading process. The choice of infeed method has a significant impact on the effectiveness of the threading. This study investigated the variations in cutting forces depending on different infeed angles and cutting areas in threading operations.

Materials and Methods

Experimental equipment

The machining experiments were performed by single point continuous turning of AISI 1050 steel specimens in cylindrical form on a Johnford TC35 CNC turning centre, with a variable spindle speed of up to 3500 rpm and a power rating of 10 kW. The workpiece specimen and thread dimensions are shown in Figure 1. Some mechanical properties and the chemical composition of the workpiece materials are given in Table 1. Coolant was not used during the experiments. Threading operations were performed on a CNC turning centre using the G76 threading cycle according to the Fanuc control system. The G76 multiple repetitive threading cycle provides a complete threading operation with 2 output blocks of information. The controller interprets the data in these 2 blocks and generates the multiple passes required to cut an entire thread. The format looks like this:

G76 Pabc Qq_1 Rr_1
G76 X... Z... Rr_2 P... Qq_2 F...
where
a = number of finishing passes as bottom of thread (02 = 2 passes).
b = chamfer amount at pull out end of thread (No chamfer = 00).
c = infeed angle of thread.

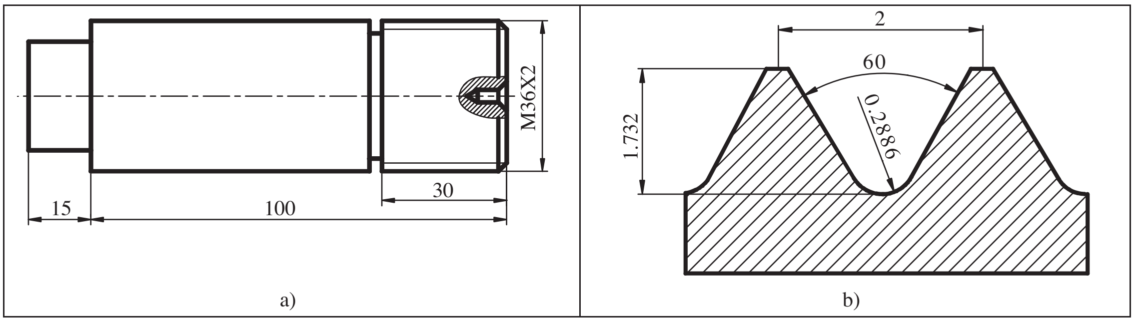

Figure 1. a) Shape of the workpiece specimen. b) Thread dimensions.

Table 1. Some mechanical properties and chemical composition of the workpiece.

Mechanical Properties		Chemical Composition (%)	
Density ($\times 1000$ kg/m^3)	7.85	C	0.5
Tensile Strength (MPa)	636	Mn	0.75
Yield Strength (MPa)	365.4	P	0.04
Hardness (HB)	187	S	0.05
		Fe	Balance

q_1 = minimum depth of cut.

r_1 = material allowance for finishing passes at bottom of thread.

X = "External thread - Minor diameter"/"Internal thread - Major diameter"

Z = end position of threaded length.

r_2 = amount of taper when cutting a tapered thread (r_2=0 for cylindrical face).

P = height of the thread.

q_2c = depth of the first cut.

F = thread pitch.

Different infeed angles can be used in threading operations, such as 0°, 14.5°, 15°, 27.5°, and 30° in this cycle. Cutting force was measured with a Kistler 9257A 3-component piezoelectric dynamometer and associated 5019 B charge amplifiers connected to a PC employing Kistler Dynoware force measurement software.

Cutting tool and cutting parameters

The cutting tool was a commercial product available from Iscar, consisting of a tool holder and indexable inserts suited to ISO 5608 and ISO 1832, respectively. The product number of the tool holder is SER 2525 M16. Each insert was clamped on a standard 25 mm shank tool holder designated SER 2525 M16 to provide a 10° clearance angle during threading. The coated carbide inserts were 16ERM AG 60 IC 908. Iscar Grade IC908 is a tough submicron PVD TiAlN coated grade. It is suitable for threading at low-to-medium cutting speeds. The cutting tool is appropriate for partial profile in metric threading operations and a new insert was used for each experiment. The cutting speed was held constant at 100 m/min as recommended by the cutting tool supplier and thread pitch was chosen as 2 mm in the experiments. The first and last pass depths must be determined by the user when using the G76 threading cycle. The amounts of these passes were also chosen according to the recommendations of the cutting tool suppliers. These values were 0.4 mm for the first pass and 0.1 mm for the last pass or finishing pass and the thread profile was obtained with 9 passes. The other amounts of passes except from the first and the last passes were fixed by cycle depending on the first and the last passes.

Infeed methods

There are 3 different types of infeed: radial, flank, and alternating flank (Figure 2). In practice the machine tool, workpiece material, insert geometry, and thread pitch determine the choice of infeed method (Metalworking, 2005). Different angles between 0° and 30° must be used to provide an accurate thread profile in metric threading by the infeed method. **A** 0° radial infeed angle is the most common for producing threads. Since the tool is fed perpendicular to the workpiece centreline radially (Figure 2 (a)) a chip is removed from both sides of thread flanks and a V-shaped chip is formed. This form of chip is difficult to break, and so chip flow can be a problem. There is a risk of vibration for coarse pitches. In addition, because both sides of the insert nose are subjected to high heat and pressure, tool life will generally be shorter with this method than with other infeed methods but both sides of the insert are subjected to cutting and so chipping does not occur. The axial movement between infeeds can be calculated simply as 0.5× the radial infeed.

The cutting edge is protected from chipping because both sides have infeed angles between 0° and 30°. The trailing edge of the insert may touch rather than the cutting edge, which can cause chipping at 30° infeed angle. In the 30° infeed method direction is parallel to one of the thread flanks. The shape of the

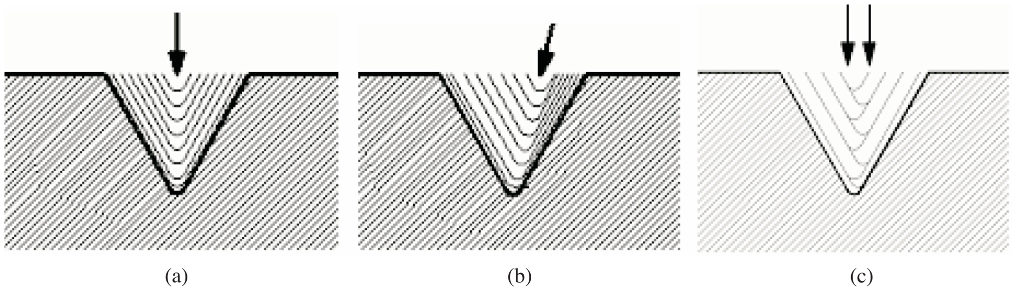

Figure 2. Infeed methods. (a) Radial infeed, (b) Flank infeed, (c) Alternating flank infeed (Metalworking, 2005).

chip is similar to what is produced in conventional turning. Compared to radial infeed, the chip here is easier to form and guide away from the cutting edge, providing better heat dissipation. However, with this infeed (Figure 2 (b)) the trailing edge of the insert touches along the flank instead of cutting. This may cause poor surface finish and chatter. The modified flank infeed method is similar to flank infeed except that the infeed angle is less than the 30° angle of the thread. This method preserves the advantages of the flank infeed method while eliminating the problems associated with the insert's trailing edge. This can result in more uniform wear (Metalworking, 2005).

In alternating flank infeed (Figure 2 (c)) the cutting insert feeds along both thread flanks and therefore it uses both flanks of the insert to form the thread. This method may provide longer tool life because both sides of the insert nose are used effectively. However, this method also can result in chip flow problems that can affect surface finish and tool life.

Results and Discussion

In tests, the cutting insert was examined after the experiments by microscope, and no tool wear was seen because of the short cutting length, as shown in Figure 1. Since infeed angle and total cutting areas affected cutting forces, at the beginning of tests the total cutting areas were calculated according to infeed angle, and the number of passes is given in Table 2.

In single point external threading operations, any infeed angle between 25° and 29.5° relative to the perpendicular to the axis of rotation is suggested for the best results (Badami, 2003). However, in this study, the optimum results were obtained at 30° infeed angle according to measured cutting forces. The main cutting force (F_c), radial force (F_r), and feed force (F_f) values according to infeed angles are given in Table 3. These values are the average of cutting forces measured through cutting length.

Table 2. The total cutting areas for different infeed angles and passes.

Total cutting areas (mm^2)									
Infeed angle (°)	Pass 1 (0.4 mm)	Pass 2 (0.2 mm)	Pass 3 (0.2 mm)	Pass 4 (0.2 mm)	Pass 5 (0.2 mm)	Pass 6 (0.2 mm)	Pass 7 (0.2 mm)	Pass 8 (0.032 mm)	Pass 9 (0.1 mm)
0	0.0924	0.1154	0.1616	0.2078	0.254	0.3002	0.3464	0.0597	0.1942
14.5	0.0924	0.1154	0.1616	0.2078	0.254	0.3002	0.3464	0.0597	0.1942
15	0.0924	0.1154	0.1616	0.2078	0.254	0.3002	0.3464	0.0597	0.1942
27.5	0.0924	0.1154	0.1616	0.2078	0.254	0.3002	0.3464	0.0597	0.1942
30	0.0924	0.1154	0.1616	0.2078	0.254	0.3002	0.3464	0.0597	0.1942

Table 3. Measured cutting forces values.

Infeed Angle (°)	Forces (N)	Passes (mm)								
		1	2	3	4	5	6	7	8	9
		0.4	0.2	0.2	0.2	0.2	0.2	0.2	0.032	0.1
0	F_f	-0.75	2.6	7.44	15.15	23.85	34.12	47.62	-59.48	23.94
	F_r	27.59	79.34	131.27	196.82	270.34	336.27	401.72	191.3	269.6
	F_c	51.05	175.83	307.12	443.29	585.59	726.19	861.59	379.84	571.51
14.5	F_f	2.11	9.38	23.81	45.99	70.58	101.59	136.54	-7.79	47.04
	F_r	31.26	84.09	133.73	196.32	266.04	327.7	396.2	174.53	265.47
	F_c	59.49	186.62	315.99	451.33	591.68	728.2	863.08	365.88	563.94
15	F_f	1.03	8.56	23.89	43.96	68.04	101.99	137.31	-13.98	38.41
	F_r	43.83	94.79	145.56	208.87	270.87	336.54	411.36	181.46	268.27
	F_c	85.95	210.11	339.09	473.15	608.5	743.64	882.62	378.14	569.31
27.5	F_f	-0.15	17.8	38.92	63.76	103.17	153.38	199.81	11.94	37.59
	F_r	32.96	79.45	123.03	168.91	224.77	285.59	342.34	152.71	237.52
	F_c	62.78	176.78	281.22	391.92	521.79	653.2	790.22	320.41	522.35
30	F_f	3.01	24.17	55.59	91.04	133.98	188.06	233	38.17	51.14
	F_r	31.43	78.93	118.26	167.3	222.22	280.56	337.75	144.3	236.26
	F_c	58.42	173.75	274.5	386.01	518.05	652.53	800.65	291.72	498.51

Table 4. Analysis of variance for main cutting force.

Source	DF	Sum of squares	Mean squares	F values	P-value
Model	12	2,477,252.59	206,437.72	776.35	< 0.0001
Infeed angle. degree	4	34,014.07	8503.02	31.98	< 0.0001
Total cutting area. mm^2	8	2,443,240.51	305,405.06	1148.54	< 0.0001
Error	32	8509.01	265.91		
Total	44	2,485,761.60			

Effects of infeed angle and total cutting area on main cutting force

The main cutting force is more important than the other forces on the cutting tool in orthogonal machining because it is higher (Shaw, 1984). In this research, the main cutting force values obtained by a machining process with a full factorial design of 5° infeed angle and 9 passes are shown in Table 3. The results of the variance analysis of main cutting force and infeed angle and total cutting area parameters are presented in Table 4. In the analysis of variance (ANOVA), the main effects of infeed angle and total cutting area depending on passes have significant effects on the main cutting force. According to the infeed angle, the lowest main cutting force was obtained by machining using the 0° infeed angle tools. The highest main cutting force was obtained using the 15° infeed angle tool.

Multiple regression analysis was conducted on the tested data. The ANOVA results of the regression model also supported linear relationships in the model (Table 4). The coefficient of determination (R^2) of the model was 0.806. The F statistic value testing utility of the model in regression analysis was 776.35. This value indicated a significance level ($\alpha < 0.01$) for the model in rejecting the null hypothesis (H_0) that every coefficient of the predictor variables in the model was zero. Instead, the alternative hypothesis, that at least one of these coefficients did not equal zero, was accepted. Therefore, a significant linear relationship between the predicted variable and predictor variables existed (Figure 3). From the ANOVA, infeed angle and total cutting area have significant effects on the main cutting force. According to the calculated coefficients of the main factors (infeed angle "a"; cutting area "b"), the multiple regression model of the main cutting force was built as shown in Eq. (1). In addition, the plot of main cutting forces versus infeed angles is illustrated in Figure 4.

$$F_c = 29.582 - 1.926a + 2318.056b \quad R^2 = 0.806 \quad (1)$$

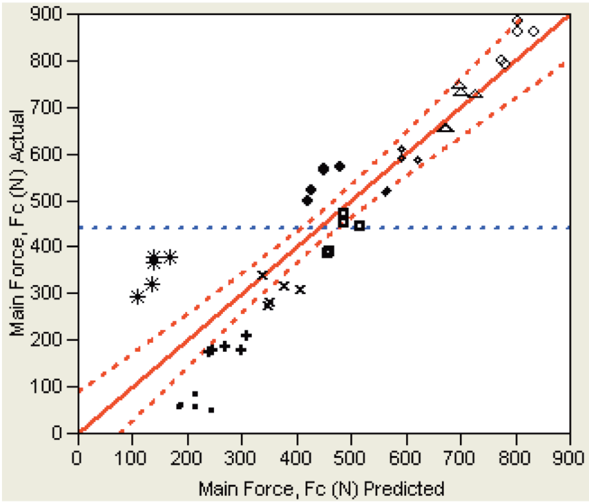

Figure 3. The plot of actual main cutting forces versus predicted main cutting forces.

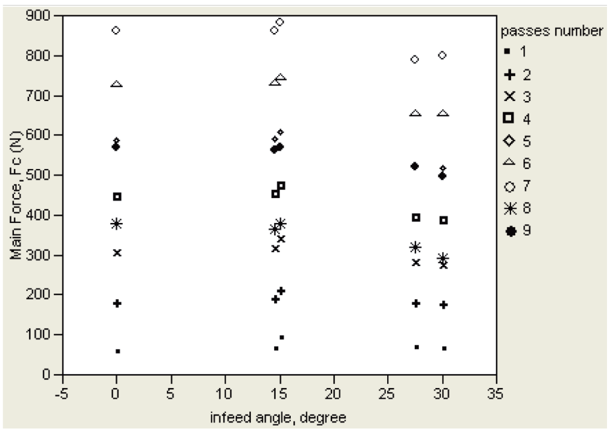

Figure 4. Main cutting force (F_c) change due to different infeed angles.

It can be seen from Figure 4 that even though the number of first passes was more than that of the other passes the main cutting force was obtained at the minimum value. This can be explained by friction from contact between the cutting tool and the workpiece and total cutting area. The friction increased due to the cutting tool machining the part with both sides, and, while the number of passes increased, the main cutting force increased too. It can be also seen from Figure 4 that the main cutting force decreased at the eighth and ninth passes. The ninth pass, with 0.1 mm, was the last or finishing operation. The main cutting force value was fourth order at the ninth pass even though the depth of the cut was lower. This can be attributed to the cutting with both sides of the insert. The amount of the eighth pass is formed according to the depth of the thread (1.732 mm) in the G76 cycle. In spite of the lowest depth of cut being at this pass the main cutting force values for all infeed angles were bigger than those for the first 3 passes. While the maximum main cutting force was obtained with 15° infeed angle in the seventh pass, the minimum value was obtained with 0° in the first pass. The uncut chip thickness and friction between cutting tool and workpiece are shared by both sides of the insert with 0°; thus the main cutting force is also shared by both sides of the insert. The main cutting force increased a little with 14.5° in comparison to 0° but a considerable increase can be seen with 15°. Most of the uncut chip thickness was cut by the main cutting edge of the insert and the other part was removed by the trailing edge with 15°. One side of the insert was exposed to more friction between the cutting tool and the workpiece; thus an unbalanced load distribution occurred and it caused an increase in the main cutting force. A considerable decrease in the main cutting force was seen in the cutting process with 27.5°. Most of the uncut chip thickness was cut by the main cutting edge and it caused gathering of loads on one side of the insert. In addition, total cutting area by the trailing edge of the insert decreased, and consequently the amount of load affecting this side also decreased in comparison to 15°. This caused decreasing of the main cutting force. The minimum total cutting area and one side cutting process with 30° caused the lowest main cutting force.

Effects of infeed angle and total cutting area on feed force

The feed force is considerable after the main cutting force in terms of cutting power or energy consumption in orthogonal cutting processes. Approximately 1% of total power is used by the feed force (Lindberg, 1990). According to experimental results the F_f/F_c ratio was 0.18 with 30° infeed angle where the feed force reached its biggest value (Table 3). Consequently it can be inferred that the feed force cannot be considered in terms of cutting power. The results of the variance analysis of feed force and infeed angle and total cutting area parameters are presented in Table 5. In the ANOVA, the main effects of infeed angle and total cutting area depending on passes have significant effects on the feed force.

The ANOVA results of the regression model also supported linear relationships in the model (Table 5). The coefficient of determination (R^2) of the model was 0.856. The F statistic value was 20.92. This value indicated a significance level ($\alpha < 0.01$) for the model in rejecting the null hypothesis (H_0) that every coefficient of the predictor variables in the model was zero. Instead, the alternative hypothesis, that at least one of these coefficients did not equal zero, was accepted. Therefore, a significant linear relationship between the predicted variable and actual variables existed (Figure 5). From the ANOVA, infeed angle and total cutting area have significant effects on the feed force. According to calculated coefficients of the main factors, the multiple regression model of the feed force was built as shown in Eq. (2). The plot of the feed forces versus infeed angles is illustrated in Figure 6. The feed force tendency increased with increasing infeed angle.

$$F_f = -94.985 + 2.454a + 546.244b \quad R^2 = 0.856 \quad (2)$$

Table 5. Analysis of variance for feed force.

Source	DF	Sum of squares	Mean squares	F values	P-value
Model	12	146,460.16	12,205.01	20.92	< 0.0001
Infeed angle. degree	4	32,426.05	8106.51	13.89	< 0.0001
Total cutting area. mm^2	8	114,034.12	14,254.26	24.43	< 0.0001
Error	32	18,673.54	583.54		
Total	44	165,133.71			

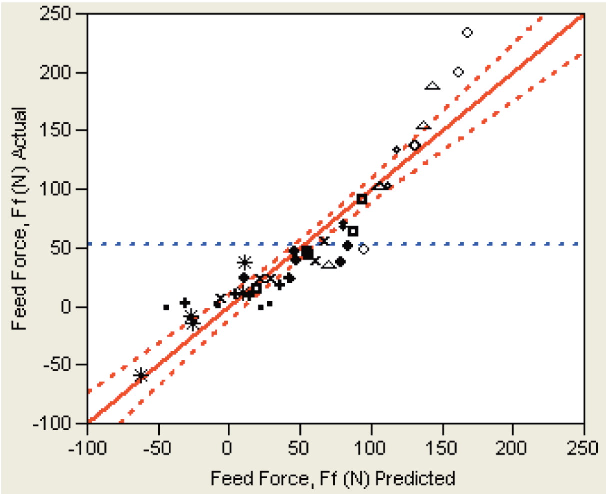

Figure 5. The plot of actual feed forces versus predicted feed forces.

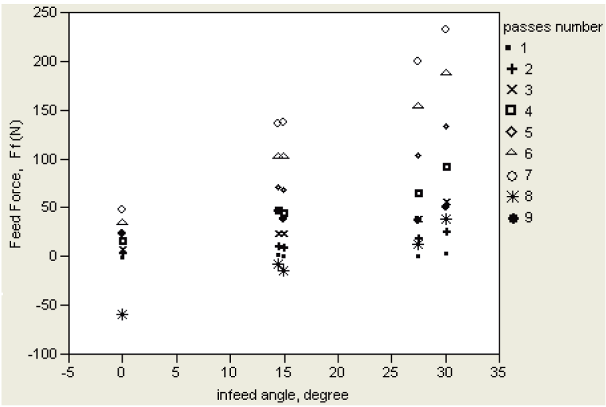

Figure 6. Feed force (F_f) change due to different infeed angles.

It is seen from Figure 6 that the feed force was not important in comparison to orthogonal cutting processes. However, the main cutting edge and the trailing edge of the insert must perform the cutting process simultaneously to produce V-shaped chip geometry in threading operations. In this process, loads affected both the trailing and main cutting edges in the feed direction in balance to each other. This balance was broken due to some reasons such as vibration, choice of cutting tool, and clamping mistakes. It can be seen from Figure 6 that the feed force has a different tendency in all infeed angles in comparison to the main cutting force. While the maximum feed force was obtained with 30° at the seventh pass, the minimum value was obtained with 0° at the eighth pass. While the difference of feed force between 14.5° and 15° was small, this difference increased after the 15° infeed angle. Most of the uncut chip thickness was removed by the main cutting edge and this caused gathering of the loads on this edge. The minimum total cutting area and one side cutting process with 30° caused the highest value of the feed force.

Effects of infeed angle and total cutting area on radial force

Radial force is as much as an average of 50% of feed force in orthogonal cutting since there is no velocity in the radial direction. Consequently, the effect of radial force on cutting power or energy consumption is inconsequential (Lindberg, 1990). According to the experimental results the F_r/F_c ratio was 0.46 with 15° infeed angle where the radial force reached its biggest value (Table 3). Consequently the radial force is important in terms of energy consumption in chip removing operations such as threading and grooving. The results of the variance analysis of radial force and infeed angle and total cutting area parameters are presented in Table 6. In the ANOVA, the main effects of infeed angle and total cutting area depending on passes have significant effects on the radial force.

Table 6. Analysis of variance for radial force.

Source	DF	Sum of squares	Mean squares	F values	P-value
Model	12	498,431.16	41,535.93	306.27	< 0.0001
Infeed angle. degree	4	11,049.49	2762.37	20.37	< 0.0001
Total cutting area. mm^2	8	487,381.67	60,922.71	449.22	< 0.0001
Error	32	4339.81	135.62		
Total	44	502,770.97			

A multiple regression analysis was conducted on the tested data. The ANOVA results of the regression model also supported linear relationships in the model (Table 6). The coefficient of determination (R^2) of the model was 0.763. The F statistic value was 306.27. This value indicated a significance level ($\alpha < 0.01$) for the model in rejecting the null hypothesis (H_0) that every coefficient of the predictor variables in the model was zero. Instead, the alternative hypothesis, that at least one of these coefficients did not equal zero, was accepted. Therefore, a significant linear relationship between the predicted variable and actual variables existed (Figure 7). From the ANOVA, infeed angle and total cutting area have significant effects on the radial force. According to calculated coefficients of the main factors, the multiple regression model of the radial force was built as shown in Eq. (3). The plot of the radial forces versus infeed angles is illustrated in Figure 8.

$$F_r = 26.830 - 1.205a + 1009.648b \qquad R^2 = 0.763 \quad (3)$$

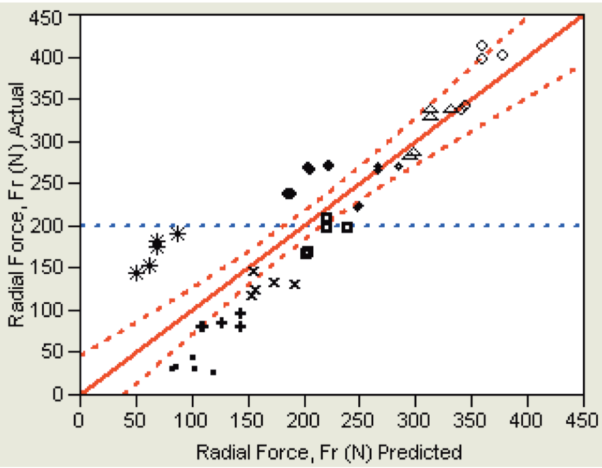

Figure 7. The plot of actual radial forces versus predicted radial forces.

Figure 8 shows that the tendency of the radial force values was similar in the main cutting force graph. While the maximum radial force was obtained with 15° infeed angle at the seventh pass, the minimum value was obtained with 0° infeed angle at the first pass. While the radial force increased a little with 14.5° in comparison to 0°, a considerable increase is seen with 15°. Most of the uncut chip thickness was removed by the main cutting edge of the insert and the other part was removed by the trailing edge with 15° and one side of the insert was exposed to more friction between the cutting tool and the workpiece. Thus an unbalanced load distribution occurred and caused an increase in the radial force. Moreover, the tendencies of radial force are similar in the main cutting force graph in respect of the total cutting area. The lowest radial force values occurred in the cutting process with 30°. This can be attributed to cutting with the trailing edge of the insert, because of decreasing total cutting area and load amount.

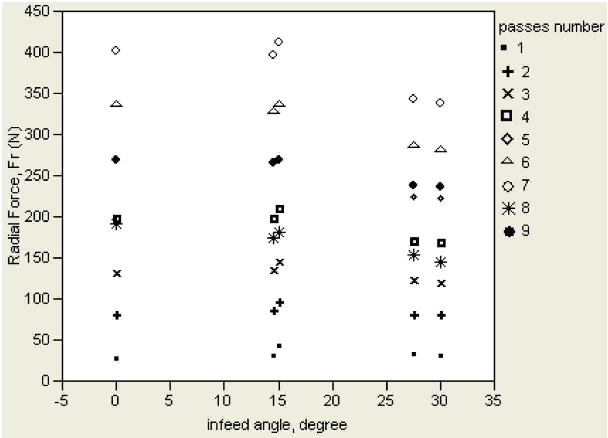

Figure 8. Radial force (F_r) change due to different infeed angles.

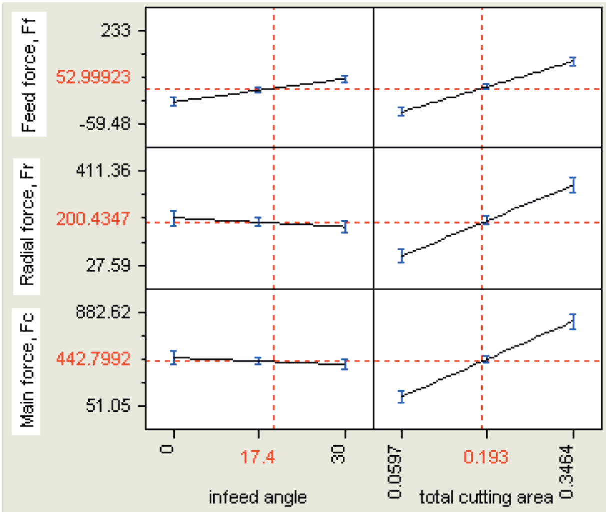

Figure 9. The main effects of infeed angle and total cutting area on cutting forces.

It can be seen from Figure 9 that the feed force has a tendency to increase while the main cutting force and radial force have a tendency to decrease with increasing infeed angle. When the cutting forces were evaluated in terms of the total cutting area; the cutting forces showed a linear increase with increasing total cutting area (Figure 9). This can be explained by friction between the cutting tool and the workpiece and total cutting area.

Conclusions

The results obtained from this study can be summarised as follows:

1. When the infeed angles were evaluated in terms of the main cutting force; the tendencies of forces were the same in all passes. However, the maximum force value was obtained with 15° infeed angle and the minimum value was obtained with 30° infeed angle. Thus it can be concluded that external threading operations are more productive with 30° infeed angle.

2. When the F_f/F_c ratio is 0.18 with 30° infeed angle the feed force reached its biggest value. Consequently it can be confirmed that the feed force had less significance in external threading operations.

3. The lowest radial force was obtained with 30° infeed angle in most of the passes. In addition, the F_r/F_c ratio is 0.46 with 15° infeed angle where the radial force reached its biggest value. According to these results, the radial force was considerable after the main cutting force in terms of cutting power in threading operations in contrast to orthogonal turning operations.

4. There is a significant linear relationship between the predicted force and actual force. The ANOVA results of the multiple regression models also supported linear relationships in the model. The model has 2 factors: infeed angle and total cutting area. Infeed angle and total cutting area have significant effects on the cutting forces. Increasing the total cutting area increased all of the cutting forces.

5. While the cutting forces increased until 15°, after that they decreased. The optimum infeed angle was 30° for external threading operations according to the cutting forces results obtained.

6. When the cutting insert was examined after the experiments by microscope, no tool wear was seen because of the short cutting length, as shown in Figure 1. Further research can be done to investigate surface quality and tool life in threading operations.

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