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A mechanistic model to predict cutting force on orthogonal machining of Aluminum 7475-T7351 considering the edge radius

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Abstract

The ploughing force related with action of edge radius is an important factor which influences flow stress, chip formation or surface integrity. Some fraction of the cutting forces are called parasitic (additional) forces and they do not contribute on chip formation process. These forces are usually assumed to be the cutting force (constant value) for zero feed. However, this effect is related with the edge radius. To improve force modelling prediction, a new mechanistic model to predict cutting force considering edge radius is presented. The model was developed for two cutting speeds and in a wide range of feeds for three edge radii. The model was validated with additional experimental tests, achieving relative errors lower than 3%.

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Keywords: Force prediction; alluminium (Al 7475-T7351); cutting edge radius; ploughing; optimization

1. Introduction

Machining is still the most relevant manufacturing operation in terms of volume and expenditure. Due to that, it is necessary to have reliable models to predict machining outcomes. Modelling of machining can be useful for improving its performance and efficiency. There exist different ways to model the machining process, such as analytical, numerical, mechanistic or hybrid approaches [1]. Mechanistic models consist of carrying out experimental tests in conditions as close as possible to the modelled ones and fitting the outcomes as function of different inputs [2]. These models, after performing the whole set of experimental tests, are more accurate and less time consuming than other approaches.

One of the most commonly used mechanistic approaches is the one proposed by Altintas et al. [3], [4] to predict the cutting forces. In this approach, the cutting force is decomposed in two terms, the first one related to the shear/cutting action and the second one related to edge effect. This second term is usually considered constant, being the value for which the fit between the force and the uncut chip thickness intercept the y-axis [5].

Nomenclature

γ	rake angle
α	relief or clearance angle
r_ε	cutting edge radius
F_c	cutting force per mm of depth of cut
K_{cc}	specific shear coefficient
K_{ce}	specific edge coefficient
K_{re}	specific edge coefficient related to edge radius
K'_{cc}	specific average shear coefficient
K'_{ce}	specific edge coefficient after the edge radius correction
f	feed
V_c	cutting speed

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However, it is well known that measured forces during cutting are not only related to the shear action as they also include some additional effects such as ploughing (factor which always occurs due to finite sharpness of the cutting tool), as it was demonstrated by Albrecth in 1960 [6], or flank friction [7]. These ploughing forces affect surface integrity (surface roughness and residual stresses increase) and reduce tool life [8]. Thus, it is necessary to take into account this effect on any model.

One of the main input parameters affecting these additional forces is cutting edge radius. Cutting tool microgeometry, which includes rake angle, relief angle or cutting edge radius, for instance, is one of the key factors to enable high performance cutting operations of any material [9]. Nevertheless, cutting edge radius has barely been studied and only some studies were found studying its effect on cutting forces, but not including it in the model. Waldorf et al. [10] proposed a slip line model to consider the ploughing effect. Thiele et al. [11], [12] studied the effect of cutting edge geometry on surface generation and residual stresses for hard turning of steel. Guo and Chou [13] used the extrapolation of cutting force to zero to estimate the ploughing force and to "correct" the material properties during metal cutting. M'Saoubi and Chandrasekaran [14] studied the effect of the microgeometry on the tool temperature, using infrared techniques. Finally, Wyen and Wegener [15] developed a comprehensive study on the effect of the edge radius on cutting forces for titanium machining.

The majority of the studies were carried out under turning conditions, neglecting low cutting speeds, typically used in broaching. In addition, to the best of our knowledge, no studies were found in which the edge radius would be directly introduced in the model.

Thus, this paper follows two main aims: investigating the ploughing effect on cutting force when machining Al 7475-T7351 under orthogonal cutting conditions and the introduction of this effect on the mechanistic model to develop a model valid for "any" edge radius.

For that, the paper is organized as follows: first, the experimental procedure is explained. Then, the experimental results are presented and discussed, and the model is presented and validated. Finally, some conclusions are drawn.

2. Experimental tests

To study the effect of cutting edge radius on cutting force, orthogonal linear cutting tests were carried out on a vertical machine center Lagun CNC 8070. The feed (uncut chip thickness in orthogonal cutting) was varied in a wide range from 0.005 to 1 mm. To study the effect of the cutting speed, two different levels of cutting speed were tested (0.5 and 30 m/min). The workpiece material was Al 7475-T7351, with 2 mm of width (depth) of cut. To measure the cutting force, a Kistler dynamometer was used (Kistler 91299AA). The workpiece was clamped to the dynamometer, whereas the tool holder was set in the spindle.

The set-up used is explained in a previous publication [16] and shown in Fig. 1. The experimental plan is summarized in Table 1. The insert was delivered by Sandvik, with a nominal edge radius of 24 μm (see Fig. 2 c). Then, the insert was systematically sharpened by grinding the relief face in order to reduce the radius of the cutting edge, to achieve 5 and 11 μm of edge radius (see Fig. 2 a) and b), in order to have three different points to study the effect of this parameter. To ensure the values of the edge radius, they were measured using Alicona IFG4 infinite focus profilometer, with an accuracy of 1 μm.

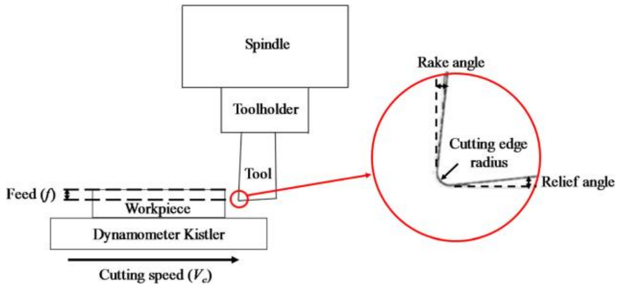

Fig. 1. Orthogonal linear set-up [16]

Table 1. Experimental plan.

Tool	Ref.	TPUN 160308
	Rake angle, γ (º)	6
	Relief angle, α (º)	5
	Coating	Uncoated
	Edge radius, r_ε (μm)	5, 11 and 24
Cutting conditions	Cutting speed, V_c (m/min)	0.5 and 30
	Feed, f (mm)	0.005, 0.01, 0.05
		0.1, 0.5 and 1
Lubrication	Type	Dry
Workpiece	Material	Al 7475-T7351
	Width (mm)	2

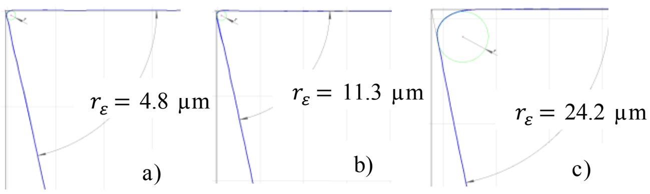

Fig. 2. Cutting edge radii tested: a) Nominal edge radius of 5 μm, b) Nominal edge radius of 11 μm and c) Nominal edge radius of 24 μm

3. Results and discussion

The cutting force at the different cutting conditions was measured with the Kistler dynamometer. The obtained results for the two cutting speeds tested are shown in Fig. 3. According to the model proposed by Altintas et al. [3], [5], the cutting force is composed by two different terms (shear action and edge action). This assumption is represented by Equation 1.

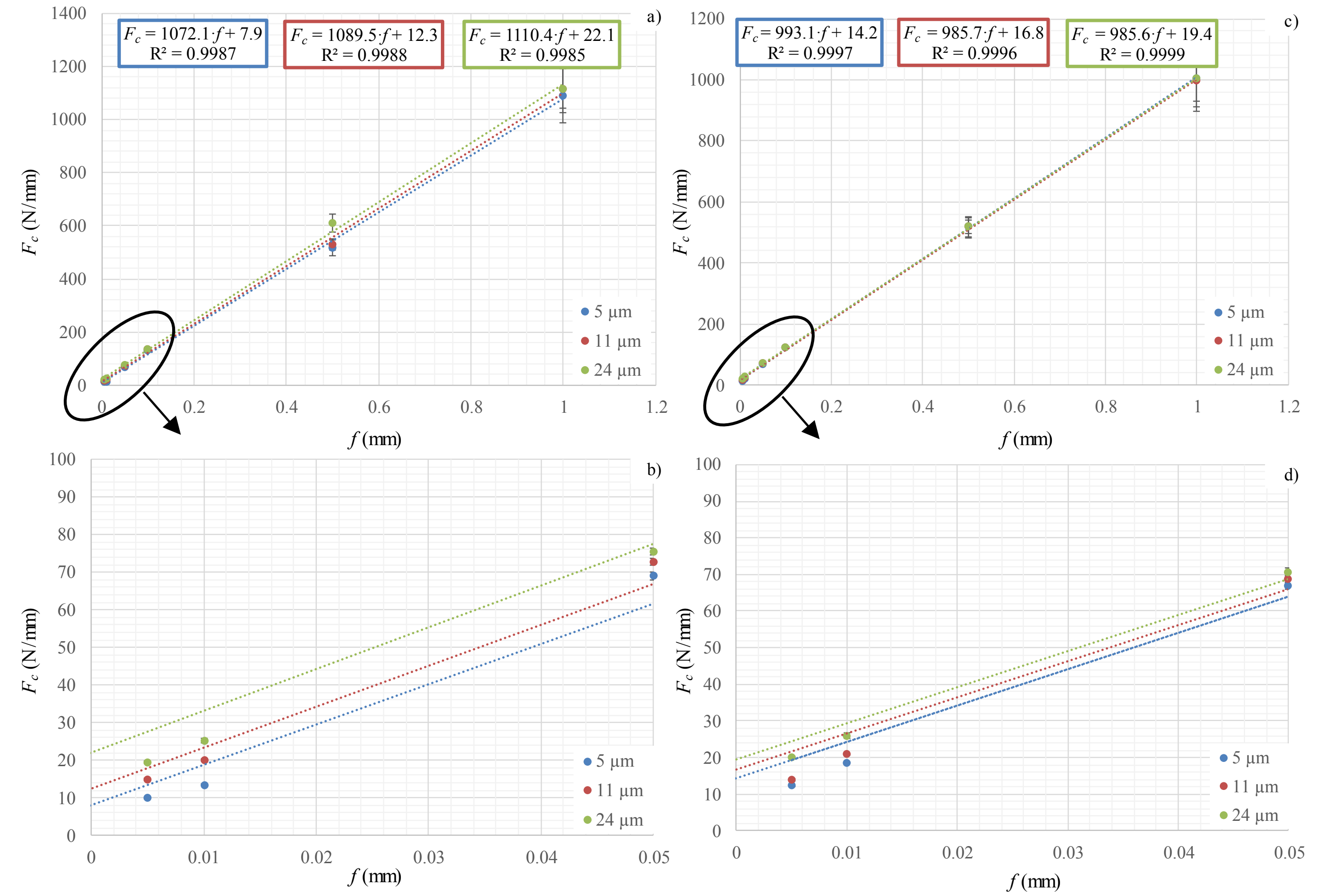

Fig. 3. a) Cutting force vs feed at $V_c = 0.5$ m/min. b) Cutting force vs feed at $V_c = 0.5$ m/min (the low feed range is zoomed in). c) Cutting force vs feed at $V_c = 30$ m/min. d) Cutting force vs feed at $V_c = 30$ m/min (the low feed range is zoomed in)

$$F_c = K_{cc} f + K_{ce} \quad (1)$$

where F_c is the cutting force per mm of depth of cut, K_{cc} is the specific shear coefficient, f is the feed and K_{ce} is the specific edge coefficient (see the intercept with the y-axis in Fig. 3 b) and d).

Based on Fig. 3 a) and c), the specific shear coefficient (K_{cc}) remains constant, not being affected by the edge radius. This behavior is equal for the both levels of cutting speed tested. This coefficient is related with the pure shear action, and it can be interpreted in terms of the shear plane [17]. Thus, it is mainly affected by the cutting conditions, such as feed or cutting speed, but not by other effects such as friction or ploughing.

In contrast, the specific edge effect (K_{ce}) is clearly affected by the edge radius. In general, the lower the cutting edge radius is (the sharper the tool), the lower the value of the specific edge coefficient is. This effect is more remarkable at low cutting speeds. In Fig. 3 b) and d), the low feed range was zoomed in, in order to highlight the importance of the edge effect at these low feeds.

The effect of the cutting speed on the edge force (K_{ce}) is not clear. For the lowest edge radius, the edge force notably increases with the cutting speed, almost two times (7.9 vs 14.2). Contrary, for the medium edge radius, this effect is less remarkable, whereas for the highest edge radius, the edge effect is reduced with the cutting speed (22.1 vs 19.4). This behavior is in accordance with the work developed by Wyen and Wegener [15].

In spite of that, the edge effect for both cutting speeds was observed to be totally linear in function of the edge radius, as it is represented in Fig. 4.

Based on the results presented in Fig. 4, the model to calculate the cutting force can be now expressed according to Equation 2.

$$F_c = K'_{cc} f + K_{re} r_\varepsilon + K'_{ce} \quad (2)$$

where K'_{cc} is the specific average shear coefficient (the average with the values at the three edge radii), K_{re} is the force component related to the edge effect and K'_{ce} is the specific edge coefficient after cutting edge correction (this value is related to other additional effects such as friction or machine vibrations).

According to Fig. 4, the additional effect that still remains after the cutting edge correction is more notable at the highest cutting speed, due to other effects (such as machine instabilities, for instance).

For the two cutting speeds, the results are summarized in Table 2.

Table 2. Obtained results.

Cutting speed (m/min)	K'_{cc} (MPa)	K_{re} (MPa)	K'_{ce} (N/mm)
0.5	1091	744	4.21
30	988.1	261.8	13.31

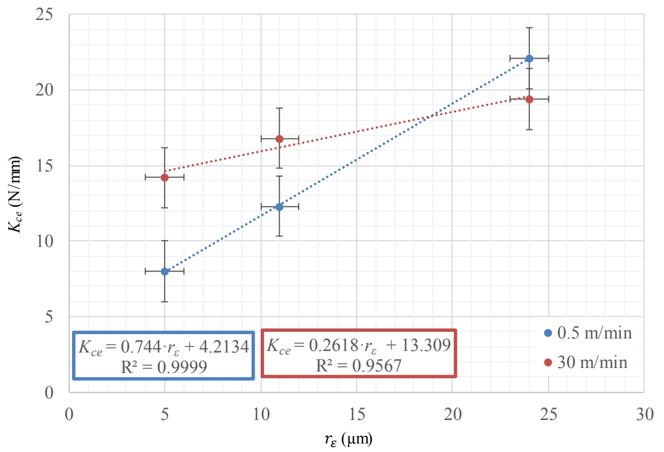

Fig. 4. Variation of the edge effect (K_{ce}) with the edge radius for both cutting speeds

According to Table 2, the order of magnitude of the effect related to the feed is comparable to the order of the one related to the cutting edge radius. This aspect is more noticeable at low cutting speeds. In Fig. 5, the effect of the edge radius to the total cutting force (represented as a percentage of the total cutting force, Equation 3, based on Equation 2 and the values of Table 2) is shown. At low feeds, the edge radius effect is more prominent.

$$\text{Edge radius effect} = \frac{K_{re} r_\varepsilon}{F_c} \cdot 100 \qquad (3)$$

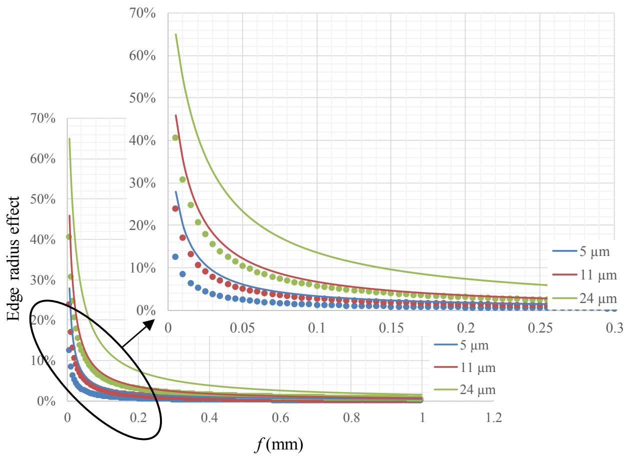

Fig. 5. Effect of the edge radius on the cutting force (V_c = 0.5 m/min represented with solid lines and V_c = 30 m/min with markers). The low feed range was zoomed in

According to Fig. 5, the effect of the edge radius is more notable at low feeds, specially lower than 0.15 mm of feed. For all the cases, there exist a change of slope (trend) when the effect is between 3% and 15%. Above this value, the effect of the edge radius decreases rapidly, but it is quite prominent on the cutting force, whereas below it the decrease is less pronounced. A feed/edge radius ratio of 6 was determined for 0.5 m/min, whereas this ratio was close to 2 for 30 m/min. That is, for 0.5 m/min, the edge radius effect starts to be negligible when the feed is more than 6 times higher than the cutting edge radius.

To prove the validity of the model proposed (Equation 2), two different cutting conditions were tested. These conditions are summarized in Table 3. The obtained results are shown in Fig. 6. Also in Fig. 6, the predictions with the model proposed were compared with the equations included in Fig. 3 a), not considering the edge correction.

Table 3. Validation conditions.

Condition Number	Cutting speed (m/min)	Feed (mm)	Edge radius (µm)
1	0.5	0.01	8
2	0.5	0.005	8

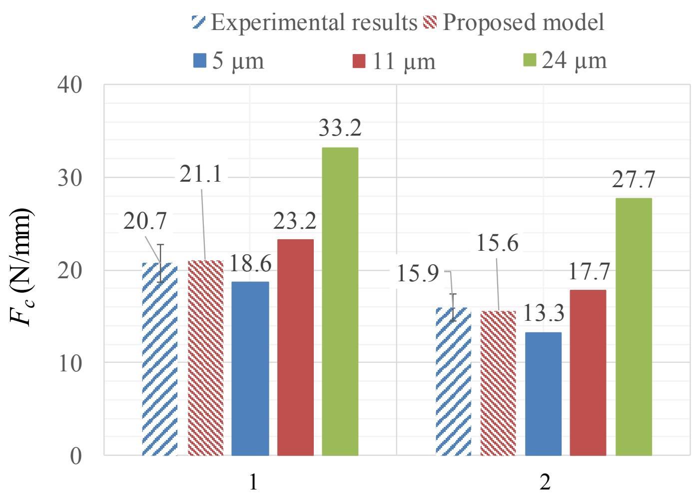

Fig. 6. Comparison between experimental validation tests and model predictions

The predicted values with the proposed model are in good agreement with the experimental ones (see Fig. 6), with the prediction error being lower than 3 % for both cases, which is a great improvement in comparison to the model shown in Equation 1. For the equation obtained with the geometry of 5 µm (see Fig. 3 a), the errors were in the range of 15%, whereas for the equation obtained with 11 µm, these errors were lower, but higher than 11%. Finally, for the highest cutting edge radius, 24 µm, as the validation edge radius is notably lower, the prediction errors were higher than 60%.

Low feeds and low cutting speeds are common in the broaching process [18–20]. Thus, it is necessary to have a good characterization of the cutting edge radius value, in order to carry out the predictions of the cutting force properly. This cutting force affects energy consumption, surface integrity and tool wear. Thus, an accurate prediction of this parameter is necessary to have a good control of the cutting process.

4. Conclusions

An extensive experimental work was carried out, covering a wide range of feeds (from 0.005 to 1 mm), cutting speeds (0.5-30 m/min) and edge radii (from 5 to 24 µm), observing that the cutting force increases with the feed (more cutting energy) and edge radius (more ploughing effect) and decreases with the cutting speed (thermal softening).

The effect of the edge radius notably decreases at high feeds. A "limit" feed/edge radius ratio of 6 and 2 were established for 0.5 m/min and 30 m/min, respectively. Thus, it can be concluded that at high cutting speeds the edge effect is lower in comparison to other additional effects. When the feed is higher than 0.15 mm, the edge effect was observed to be negligible. This could lead one to think that this effect is not relevant. However, at low feeds and low cutting speeds, the effect of the cutting edge is remarkable, corresponding to more than 40% of the total force in some cases. These conditions may not be relevant to high feed processes, such as turning, where the edge radius effect could be neglected, but they are characteristic of processes such as broaching.

Finally, the proposed model, which combines the shear action, the edge radius action and the additional (parasitic) effect was observed to be accurate, with a prediction error lower than 3% (relative error) for the two validation conditions tested. Thus, with this way of modeling the edge radius, it may not be necessary to carry out the characterization (the whole set of orthogonal cutting tests) for each different edge radius, simplifying the way of modelling the cutting force and improving the accuracy of the predictions.

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