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Investigations on the influence of radial run-out on cutting forces for serrated cutters

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Abstract. Serrated cutters with their complex local tool geometries result in continuously changing chip thickness and engagement conditions due to a change in local radius along the serration height. This change in geometry results in a reduction of cutting forces, and hence these cutters are favoured in the rough cutting of difficult-to-cut materials. The change in local radius of the cutter is also influenced by the radial run-out on the tool. Run-out, though undesirable, is inevitable. How this run-out influences the local radius, chip thickness, and forces, is not entirely understood for serrated cutters. This paper fills that gap, by presenting a model that factors in the influence of radial run-out on cutting forces for serrated cutters. Investigations with different sets of cutting parameters shows that for cutting with a low feed, and high axial and radial depths of cut, the influence of run-out on the cutting forces is negligible. For the case of cutting with high feeds however, we find that run-out adversely impacts cutting forces for any combination of axial and radial depths of cut. We also observe that with certain combinations of cutting parameters and run-outs, serrated cutters loose their advantage over regular end mills with similar levels of run-outs. Our findings suggest that serrated cutters may be used even with high levels of run-outs when the feed is low, and that their use should be avoided for any level of run-out when cutting with high feed rates.

Keywords: Serrated Cutters, Run-out, Chip Thickness, Cutting Forces

1. Introduction

Serrated cutters with their complex local tool geometries result in continuously changing chip thickness and engagement conditions due to a change in local radius along the serration height. This change in geometry results in a preferential reduction of cutting forces, and hence these cutters are favoured in the rough cutting of difficult-to-cut materials. The change in local radius of the cutter is also influenced by the radial run-out on the tool. Run-out is characterized as the difference in the geometrical axis of the tool from the spindle's rotational axis. Run-out, though undesirable, is inevitable due to how the tool is clamped in the tool holder, and also due to manufacturing tolerances, and errors. How this run-out influences the local radius, chip thickness, and forces, is not entirely understood for serrated cutters. The main focus of this paper is hence to incorporate run-out in predictive force models for serrated cutters, and present systematic investigations on how different levels of run-out influence cutting forces for serrated cutters for different combinations of cutting parameters.

Since run-out changes the nature of cutting forces, and contributes to surface roughness errors on machined workpieces, and also contributes to premature tool wear and potential breakage of the tool, a lot of research attention has been paid on modelling and understanding the influence of run-out for milling cutters. Early seminal work by Martellotti [1-2] reported on the influence of run-out in milling processes. Later, Kline and DeVor [3] presented mathematical models incorporating the influence of run-out on force prediction for regular end mills. Zheng et al. [4] reported on face milling force profile changes with run-outs. M. Wan et al. [5] proposed new techniques to calibrate cutting force coefficients and run-out parameters in peripheral milling. The effect of run-out on cutting force variation and surface roughness generation was also studied by M. Krüger and B. Denkena [6], in which they identified run-out parameters from measured process forces using model-based run-out identification methods. Schmitz et al. [7] explored the effect of milling cutter run-out on surface topography, surface location error, and stability in end milling operations. More recently, Li et al. [8] addressed the issue of run-out in five-axis milling processes. Most literature addressing the influence of run-out in milling, has focused only on regular end mills, and even though run-out is an important factor for end mills with serrations, the reported research on serrated end mills has focused more on modelling the serration geometry and its influences, than on run-out.

Some classical early work on straight fluted serrated end mills was presented by Tlusty et al. [9], in which it was shown that due to the reduced contact between the tool and the workpiece on account of serrations, cutting forces reduce. Merdol and Altintas [10-11], and Dombovari et al. [12] reported modelling of cylindrical and tapered serrated end mills with a generalized representation of serration profiles using cubic-splines without considering the effect of run-out. Later, Campomanes [13] presented a detailed mechanics based model that included the influence of helix with sinusoidal serrations, and used an approximate chip thickness model. He also made passing reference to how run-out does not have a significant effect on the cutting forces for serrated end mills at lower feed rates. His work however, or the work of others before, and/or after him, does not support the claim based on model based systematic investigations. Since serrated cutters preferentially reduce cutting forces, the influence of run-out on cutting forces, if any, and if run-out negates the positive influence of serrations in reducing forces, needs to be understood comprehensively based on systematic model based investigations, and is the main motivation of the present work.

We present an expanded geometric model for serrated cutters that includes the influence of radial run-out, in Section 2. We limit our discussions in this paper to serrations only of the sinusoidal kind. We ignore axial run-out presently. We also assume that run-out is measurable on serrated tools. Measuring run-out on regular end mills is possible, and has been reported on elsewhere, see for example [14-16]. However, measuring run-out on serrated cutters due to constantly changing radius along the serration wavelength is non-trivial, and needs to be addressed separately. Assuming run-out to be measurable, we systematically investigate its influence on force profiles for different combination of cutting parameters in Section 3. We systematically discuss the influence of run-out for different levels of feed, and axial and radial depths of cut. This is followed by the main conclusions in Section 4.

2. Geometric Model of Serrated Cutter with Run-out

This section describes the geometry of serrated cutters considering the influence of radial run-out. Models described in this section build on the classical work done by Merdol and Altintas [11], and by Dombovari et al. [12], and also on our own earlier reported work [17], by inlcuding the infleunces of run-out.

2.1. Modelling of Serration Profile

A schematic, and a cross-sectional view of a sinusoidal serrated cutter with run-out is shown in Fig. 1. Due to the run-out, cutter geometrical centre, denoted by O_g deviates from spindle rotation centre O_r, by a constant radial deviation, ρ. The run-out angle between direction of radial offset (deviation) and the nearest tooth at the bottom of the tool is denoted by δ. We assume that there is no axial run-out or any cutter geometric axis tilt, i.e ρ is constant along the cutter height. Due to the run-out, since the whole system rotates about the spindle axis through O_r, it is convenient to model all things with respect to O_r, and hence the *xyz* coordinate frame is attached to O_r as shown.

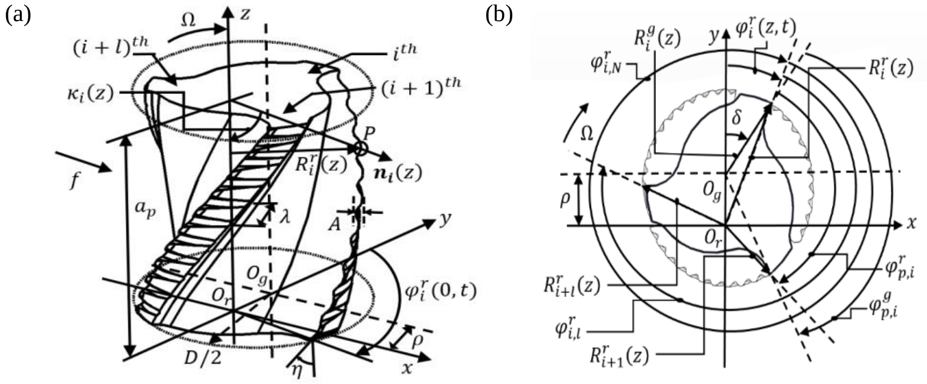

Fig. 1. (a) Geometry of the serrated cutter with run-out. Figure is adapted and modified from [17] (b) Cross-sectional view at height z with run-out.

The cutter can have N number of flutes (teeth), but as an example, only three (i^{th}, $(i+1)^{th}$ and $(i+l)^{th}$) flutes are shown in Fig. 1. As there is a wavy surface along the flute of the serrated cutter, the local geometrical radius changes along the flute and the height. The local geometrical radius which is measured with respect to geometrical axis (dotted line through O_g shown in Fig.1(a)) which is parallel to *z* axis for the i^{th} flute at the height *z* is defined as:

$$R_i^g(z) = \frac{D}{2} - \Delta R_i^g(z) \tag{1}$$

wherein D is shank diameter (nominal diameter) of the cutter, and $\Delta R_i^g(z)$ is the variation in local geometrical radius for the sinusoidal serration profile:

$$\Delta R_i^g(z) = \frac{A}{2} - \frac{A}{2}\, sin\left(\frac{2\pi z}{\lambda\cos\eta} - \psi_i + \frac{\pi}{2}\right) \tag{2}$$

wherein A is the serration amplitude, which is half of the peak to peak serration height; λ is the wavelength; η is the helix angle; and ψ_i is the phase shift due of the serrations on different flutes, explained in [17]. All geometries are measured with respect to spindle rotational axis which do not align with cutter geometrical axis due eccentricity between them caused by the run-out. Due to the run-out, we define another local radius called the rotational radius with respect to the z axis through O_r as follows:

$$R_i^r(z) = \left[\left(\rho + R_i^g(z)\, cos\left(\delta - \sum_{k=1}^{i-1} \varphi_{p,k}^g - \frac{2z\tan\eta}{D}\right)\right)^2 + \left(R_i^g(z)\, sin\left(\delta - \sum_{k=1}^{i-1} \varphi_{p,k}^g - \frac{2z\tan\eta}{D}\right)\right)^2\right]^{0.5} \tag{3}$$

The local geometrical radius $R_i^g(z)$ for a representative four-fluted sinusoidal serrated cutter without and with run-out is shown in Fig. 2(a), and Fig. 2(b), respectively. Cutter parameters are as follow: shank diameter D=16 mm, serration amplitude and wavelength, $A = 0.38$ mm, $\lambda = 1.8$ mm; and, helix angle η =20 degree. Run-out is assumed as $\rho = 50\ \mu m$ and $\delta = 30$. Comparing Fig. 2(a) and (b) we see that run-out makes the radius irregular.

(a) (b)

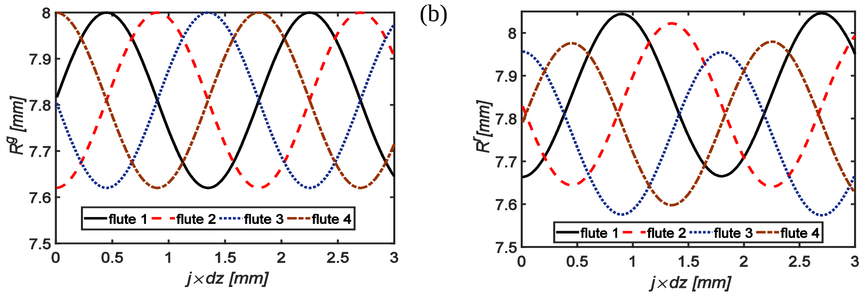

Fig. 2. (a) Variation of local geometrical radius, R^g along height without run-out, (b) Variation of local rotational radius, R^r along height with run-out: $\rho = 50\ \mu m, \delta = 30°$.

In addition to causing a change in the local radius, run-out also changes the instantaneous radial immersion angle. The angular position for the i^{th} flute at height z, measured from the y axis in a clockwise direction considering the run-out, called the instantaneous radial immersion angle, is calculated as follows

$$\varphi_i^r(z,t) = \Omega t + \sum_{k=1}^{i-1} \varphi_{p,k}^r - \frac{2z\tan\eta}{D} \tag{4}$$

wherein, Ω is the clockwise spindle speed (rad/sec) and $\varphi_{p,k}^r$ is new pitch angle with respect to O_r due to the run-out. The relationship between the new pitch angle $\varphi_{p,k}^r$ with respect to O_r and the old geometrical pitch angle $\varphi_{p,k}^g$ with respect to O_g are shown in Fig. 3(a). From Fig. 3(a), using the cosine triangle formula, $\varphi_{p,k}^r$ is calculated as follows:

$$\varphi_{p,k}^{r} = \cos^{-1}\frac{\left(R_i^r(z)\right)^2 + \left(R_{i+1}^r(z)\right)^2 - \left(L_i^r(z)\right)^2}{2R_i^r(z)R_{i+1}^r(z)} \tag{5}$$

wherein,

$$L_i^r(z) = \sqrt{\left(R_i^g(z)\right)^2 + \left(R_{i+1}^g(z)\right)^2 - 2R_i^g(z)R_{i+1}^g(z)\cos\varphi_{p,k}^g}$$

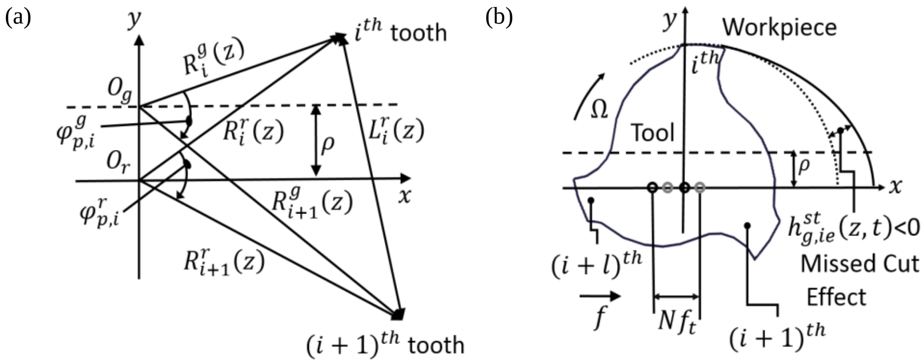

Fig. 3. (a) Calculation of the new rotational pitch angle, $\varphi_{p,k}^{r}$ due to the run-out on serrated cutters (b) Missed cut effect with run-out for serrated cutter

In addition to a change in the instantaneous radial immersion angle, and pitch angles, run-out also changes the axial immersion angle, and that is calculated as detailed in [17]. Furthermore, the changed pitch angle, due to run-out, may result in a delay between formation of the current surface being generated and the previous surface generated, due to which, re-distribution of multiple delays may occur, and this can be factored in as discussed in [17], and as discussed next in Section 2.2.

2.2. Local Chip Thickness

Elemental physical static chip thickness is defined as the local distance between previous and current cut surface in the direction of normal vector $\boldsymbol{n}_i(z)$ of the flute considering run-out with circular tool path approximation as:

$$h_i^{st}(z,t) = g_i(z,t)\min_{l=1}^{N}[(R_i^r(z) - R_{i+l}^r(z)) + f_{i,l}(z,t)\sin\varphi_i^r(z,t)]sin\,\kappa_i(z) \tag{6}$$

wherein $f_{i,l}(z,t)$ is the corresponding feed motion during delay time $\tau_{i,l}$, $\kappa_i(z)$ is the axial immersion angle, $g_i(z,t)$ the screening function due to radial immersion and missed cut (Ref. Fig.3(b)) effect, explained in [17], and $R_i^r(z)$ is calculated from Eq. (3). The missed cut effect considering the run-out, creates a non-uniform chip thickness profile as shown schematically in Fig. 3(b).

Variation in the chip thickness profile for a four-fluted sinusoidal serrated cutter considering zero run-out is shown in Fig. 4(a) and considering run-out ($\rho = 50\,\mu m, \delta = 30°$) is shown in Fig. 4(b). The cutting conditions chosen are: depth of cut, a_p=3 mm, feed, f_t =0.25 mm/tooth, and speed, 5000 rpm, for slotting, i.e.100% immersion. Comparing Fig. 4(a) and (b) we see that due to the run-out, the flute chip thickness for the 1st and 2nd flutes increases by 150%, and for the other two flutes, it decreases by 5%. Since chip thickness is different with run-outs, cutting forces which depend on chip thickness, are also expected to be different.

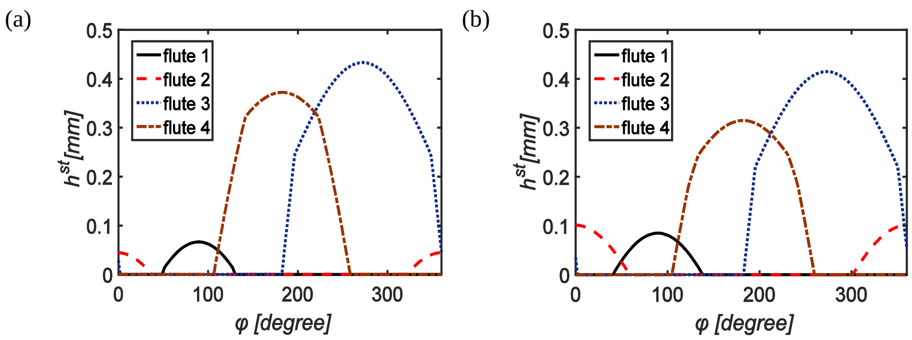

Fig. 4. Chip thickness (h^{st}) distribution at tool tip ($z = 0\ mm$) (a) without run-out (b) with run-out: $\rho = 50\ \mu m, \delta = 30°$

The force model presented in [17] is used incorporating Eq. (6) to investigate the influence of run-out on force profiles, as discussed next, in Section 3. Furthermore, since the chip thickness also depends on the instantaneous entry and exit angles, these too will change with run-out, and they will also result in the force model being updated. However, for brevity, those formulations are not reported herein, since we observed that even without the updated entry and exit angle formulations, the force profiles do not change much.

3. Effect of Run-Out for Serrated Cutter at Different Operating Conditions

In this section, we discuss the influence of run-out on cutting forces for different combination of cutting parameters. Our serrated cutting force model without run-out was numerically verified against other reported results, and was also experimentally validated in our earlier reported work in [17]. We have also numerically verified our run-out model, albeit for the regular end mill case (i.e. by putting $A = 0$ in force model), using a commercially available advanced machining process simulation software, CutPRO [18], but have not reported those results here for brevity. Herein we only present numerical investigations for our serrated model with run-out.

Although serrated cutters are more effective at reducing forces with low feeds than at high feeds, the effect of run-out is investigated for all possible operating conditions. Two types of feeds, one low (0.02 mm/tooth), and, the other, high (0.25 mm/tooth) are chosen. We present results with a low feed in Section 3.1, and present a subset of results with a high feed in Section 3.2. At each feed, two levels of engagement conditions, one low (10% up milling), and, the other, high immersion (100% slotting) are taken. Again, for each engagement condition, two levels of depths of cut, one low (a_p= 3mm), and, the other, high (a_p= 8mm) are chosen. Other cutting conditions for all cases are as follow: run-out angle $\delta = 30°$, 5000 rpm, helix $\eta = 20°$. For each case, cutting force is compared for zero run-out, small run-out ($5\mu m$) and large run-out ($50\mu m$), as discussed in subsequent subsections. To also understand, how/if run-out on serrated cutters can potentially negate the positive influence of serrations, which is to otherwise reduce force, we also discuss in Section 3.3, results for regular end mills with run-outs.

3.1 Influence of run-out at low feed (0.02 mm/tooth) rates

Effect of run-out on serrated cutting forces (F_x) at low feed (0.02 mm/tooth) rates is shown in Fig. 5. From Fig. 5, we observe that the ratio of maximum to average force increases with an increase in run-out. Maximum difference occurs between zero run-out and large run-out force profiles. For 10% up milling, at a low depth of cut (a_p= 3mm) (Fig. 5(a)), the increase of the peak amplitude of up to 25% from the case of zero run-out is observed, and at a high depth of cut (a_p= 8mm) (Fig. 5(b)), the increase of the peak amplitude of up to 12% is observed. For 100% milling (slotting) at a low depth of cut (a_p= 3mm) (Fig. 5(c)), the increase of the peak amplitude of up to 13% is observed, and at a high depth of cut (a_p= 8mm) (Fig. 5(d)), the increase of the peak amplitude of up to 10% is observed.

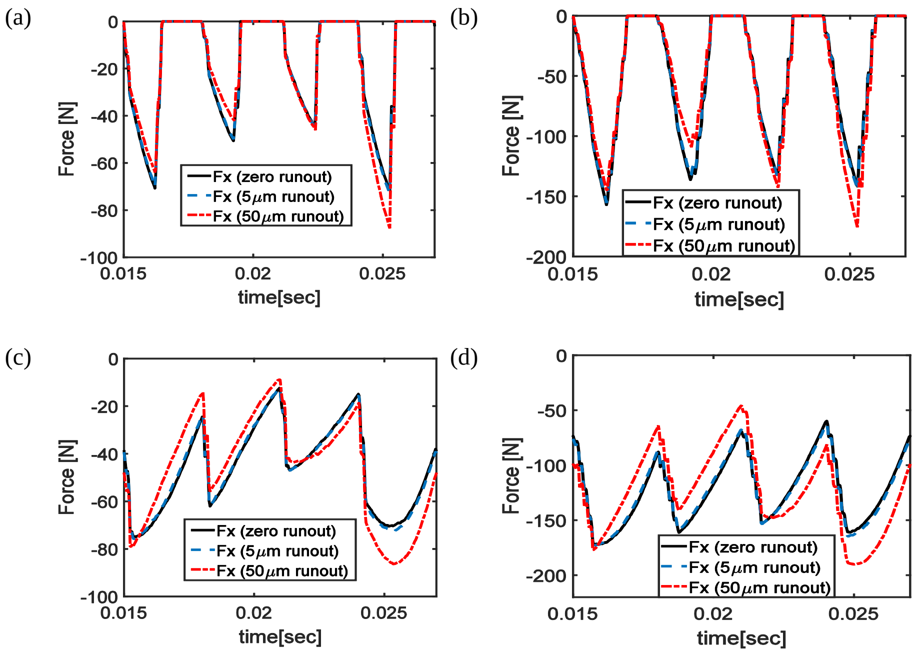

Fig. 5. Influence of run-out on cutting force (F_x) for a sinusoidal serrated end mill for low feed rates: (a) a_p= 3mm, at 10% up milling (b) a_p= 8mm, at 10% up milling; (c) a_p= 3mm, at 100% milling (slotting) (d) a_p= 8mm, at 100% milling (slotting)

From these investigations, we can conclude that at low feeds, there is no substantial increase in the maximum force, or a significant change in the force profile, even with large values of run-out. This is interesting, and is consistent with the insightful observations made in passing by Campomanes [13]. We also see that for the cases investigated, there is no significant change in the mean value of the forces, even with large run-outs on serrated cutters. These observations suggest that serrated end mills may be used even with large run-outs on them at low feeds, and potentially any combination of axial and radial depths of cuts, without resulting in any potentially significant damage to the tool, or the surface profile.

3.2 Influence of run-out at high feed (0.25 mm/tooth) rates

Effect of run-out on serrated cutting forces (F_x) at high feed (0.25 mm/tooth) rates is shown in Fig. 6. Here we report on only a subset of the cutting combinations reported on in Section 3.1. As before, in this case too, we observe that the ratio of maximum to average force increases with an increase in run-out. For 10% up milling at low depth of cut (a_p= 3mm) (Fig. 6(a)), the increase of the peak amplitude of up to 35% is observed. For the 100% milling (slotting) at high depth of cut (a_p= 8mm) (Fig. 6(b)), the increase of the peak amplitude of up to 25% is observed.

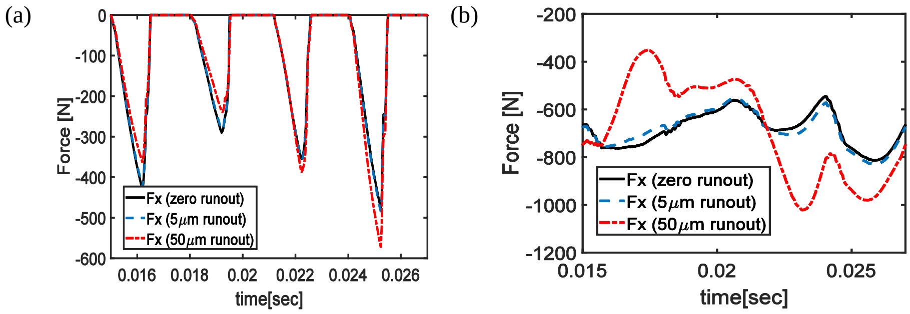

Fig. 6. Influence of run-out on cutting force (F_x) for sinusoidal serrated end mill for high feed rates: (a) a_p= 3mm, at 10% up milling; (b) a_p= 8mm, at 100% milling (slotting)

Contrasting the results for high immersion with those of the low immersion case, we see that with high feed rates and for low immersion cutting, run-out appears to have a more severe effect than at the high feed and high immersion case. Moreover, for the high feed and high axial and radial depths of cut, there is also a significant change in the force profile for high levels of run-out as comapred to the case of zero run-out. These observations suggest that if serrated cutters have high levels of run-out, they best be avoided to be used with high feed rates. Since the sudden increase in forces, may cause impact loading on the cutter, which may cause it to prematurely break.

Seeing that serrated cutters with high run-outs are not advisable to use with high feed rates, to understand if/how run-out on serrated cutters used at high feed rates can potentially negate the positive influence of serrations, which is to otherwise reduce forces, we discus results for regular end mills with run-outs next in Section 3.3, and contrast those findings with those observed here.

3.3 Influence of run-out at high feed (0.25 mm/tooth) rates for regular end mills

Effect of run-out on regular end mill cutting forces (F_x) at high feed (0.25 mm/tooth) rates is shown in Fig. 7. Here too, we report on only a subset of the cutting combinations reported on in Section 3.1. Results herein are obtained by setting $A = 0$ in the force model, i.e. essentially making it a regular end mill. All other geometry is the same as for the serrated end mill. As observed for serrated end mills, we observe that the ratio of maximum to average force increases with an increase in run-out. As evident in Fig. 7, for 10% up milling at a low depth of cut (a_p= 3mm) (Fig. 7(a)), the increase of peak amplitude of up to 37% is observed, whereas for 100% milling (slotting) at a high depth of cut (a_p= 8mm) (Fig. 7(b)), difference of the peak amplitude up to 46.5% is observed. These observations, as before, suggest that if regular end mills have high levels of run-out, they best be avoided to be used with high feed rates.

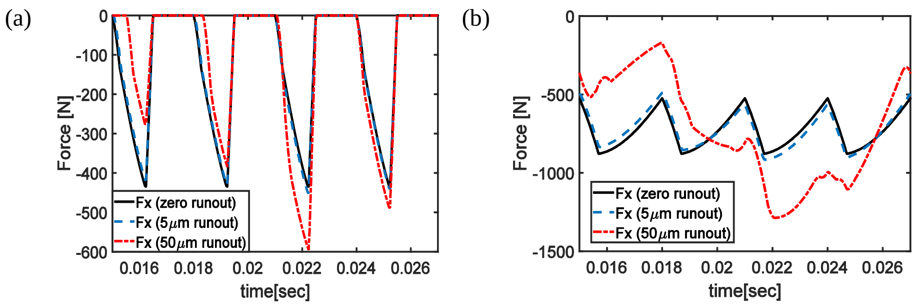

Fig. 7. Influence of run-out on cutting forces (F_x) for regular end mill at high feed rates: (a) a_p= 3mm, at 10 % up milling; (b) a_p= 8mm, at 100% milling (slotting)

Comparing the results for serrated cutters with run-out and with cutting at high feed and low immersion in Fig. 6(a) with those in Fig. 7(a) for regular end mills with run-out and high feed, with also low immersion, it is clear that even in the case of no run-out, the maximum force for the serrated end mill considered, is 11% higher than regular end mills, which suggests that serrated cutters are ineffective at high feed rates, since there is no preferential reduction in cutting forces. The trend however reverses for the case with large run out, which is strange, and needs to be investigated further. For the case of serrated end mills cutting with high feed, and high immersion (axial, and radial), the peak force from Fig. 6(b) is lower than the case of regular end mills from Fig. 7(b), without and with large run-outs. These observations are interesting, and suggest that at certain combination of cutting and run-out parameters, serrated end mills retain their advantage over regular end mills, while at certain other combinations of cutting and run-out parameters, serrated cutters loose their advantage over regular end mills.

4. Conclusions

This paper discussed the influence of run-out on serrated cutters. We expanded the geometric force model for sinusoidal serrated cutters by including the effect of run-out. We systematically investigated how the run-out influences local chip thickness distribution, and how that in turn can potentially change the force profile for serrated cutters with run-out. Comprehensive investigations on the influence of run-out on forces were presented for a combination of feed rates, and axial and radial depths of cut. We observed that high levels of run-out increase the ratio of maximum to average forces, and also change the nature of the cutting force profile. Interestingly, we observed that at low feeds, and large axial and radial depths of cut, run-out had no significant effect on the serrated force profiles, suggesting that even for large levels of run-outs, serrated cutters may still be used with low feed and high axial and radial depths of cuts, without worrying too much about if run-out may damage the work piece quality, or cause tool breakage. For cutting with high feed rates however, we observed that run-out adversely impacts cutting forces for any combination of axial and radial depths of cut. We also observed that with certain combinations of cutting parameters and run-outs, serrated cutters loose their advantage over regular end mills with similar levels of run-outs, and hence their use in such cases should be avoided.

Our findings were only for the case of sinusoidal serrations, and having neglecting axial run-out. How run-out potentially influences force profiles for other serration types needs to be also investigated. Furthermore, numerical investigations presented herein need experimental validation, which will also include actually measuring run-out on serrated cutters, and these form part of our planed future investigations.

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