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Design of Serrated End Mills for Improved Productivity

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Abstract

Cutting forces continues to be a major limitation in machining operations. In order to avoid high cutting forces, low feed-rate or low axial/radial can be utilized which decrease the productivity. Special end mills such as serrated or crest-cut milling tools can be used in roughing operations to decrease the cutting forces and increase the productivity. In this work, mechanics of serrated end mills are modeled. Moreover, effects of serration shapes on the mechanics of milling are investigated and methods for designing optimum serration shapes are presented. Proposed model predictions are verified through experiments.

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Keywords: Cutting Forces; Special End Mills; Serrated Tools; Genetic Algorithm

1. Introduction

Industry increasingly demands high productivity in today's competitiveness environment. One of the most important processes is milling which is based on the removing of material from bulk parts in the form of chip by using shearing mechanism. In order to satisfy the requirements of industry in terms of productivity, milling process should be done with high material removal rate. High material removal rate is achievable in stable condition which means that the processes should be done with reduced cutting forces and higher stability limits. In order to obtain chatter free cutting condition deep stability lobes in higher cutting speeds can be used. But due to machinability or machine limitations working in high cutting speeds is not possible in all cases. Special end mills, such as variable helix/pitch or serrated tools, are enhanced to reduce cutting forces and increase stability limits in lower cutting speeds. In the Figure 1 the general view of the serrated end mills is illustrated.

Although significant number of studies has been done in modelling of the mechanics and dynamics milling process with regular end mills, there are not many works about milling with serrated end mills.

Tlusty and Zaton [1] focused on the chatter stability of the end mills with serrated straight flutes. In the parallel to this research, Campomanes [2] presented a model for mechanics and dynamics of serrated tools with sinusoidal serration form. In this model the effect of full geometry did not take to account and milling forces are calculated with linear edge force model which proposed by Budak et al. [3]. Merdol and Altintas [4] proposed a model for serrated end mills. In this model, a spline has been fitted to the serration wave. Moreover, a time domain solution for the stability was presented.

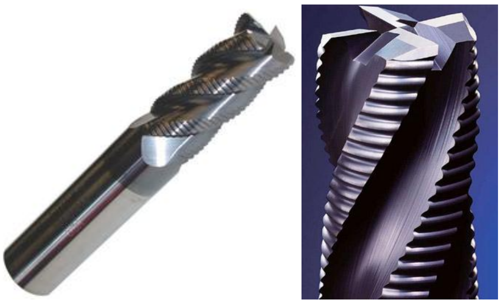

Figure 1. General view of the serrated end mills

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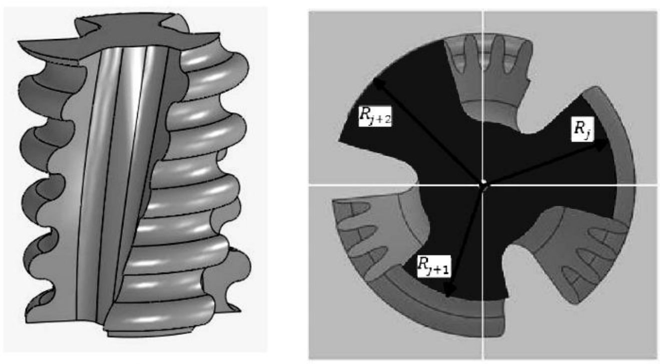
In the present study, common serration waves shapes, i.e. sinusoidal, circular and trapezoidal are defined by their geometrical parameters in order to show their effects on results. Moreover, mechanics of milling with serrated end mills is modeled using the linear edge force model [2] and the model is verified by the experiments. In addition, it is shown that the serration parameters have significant effect on the milling forces. Finally, the optimum shape of the tool is defined by using Genetic Algorithm.

2. Geometry

In the serrated tools, each tooth has wavy flank surface along its edge. Moreover, waves in the consecutive teeth have phase difference. As a result, tool radius changes along axial direction and it is not constant for each edge at any level (Figure 2). Therefore, the contact length between work piece and cutter is decreased. This is the main mechanism behind cutting force reduction in milling with serrated end mills. The local radius can be calculated by considering the serration wave form.



a) b)

Figure 2. a) The effect of serration waves on local tool radius, b) cross-section of a serrated end mill

2.1 Sinusoidal serration form

This type of serration is defined by a sine wave with amplitude A and wave length of λ. For sinusoidal serrated tools local radius of tooth j at level z can be obtained by equation (1) .

$$R_j(z) = R - A + A(\sin(\gamma(z,j))$$
$$\gamma(z,j) = 2\pi(\frac{z/\cos(\beta_j)}{\lambda}) - ps(j) \quad (1)$$

Where γ(z,j) shows the angle of the serration in the j^{th} tooth at level of z. ps(j) shows the phase shift of serration wave from the zero phase sine wave on tip of the j^{th} tooth. R is the tool radius.

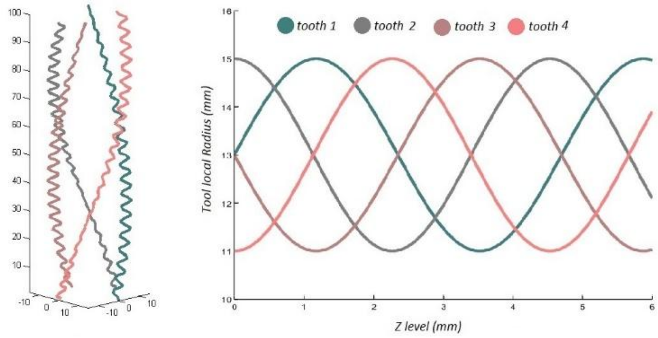


Figure 3. . Schematic view of an end mill with the sinusoidal serration and variation of local radius along tool axis

2.2 Circular serration form

This type of serration includes two arcs of two circles as shown in Figure 4. The Local radius for each tooth at any level is calculated and its variation is shown in Figure 5.

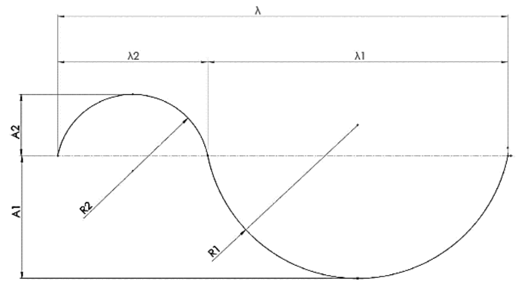


Figure 4. Circular serration wave parameters

The local radius of each tooth in level z in this type of serration can be calculated by equation (2).

$$\lambda_1 = 2\sqrt{A_1(2R_1 - A_1)}$$
$$\lambda_2 = 2\sqrt{A_2(2R_2 - A_2)}$$
$$\lambda = \lambda_1 + \lambda_2$$
$$\gamma(z, j) = 2\pi\left(\frac{z/\cos(\beta_j)}{\lambda}\right) - ps(j)$$
$$x = \mathrm{Rem}\left(\frac{\gamma(z, j)}{\lambda}\right)$$
$$if \begin{cases} x < \lambda_1/2 \\ x \geq \lambda_1/2 \\ x < \lambda_1 + \lambda_2/2 \\ x \geq \lambda_1 + \lambda_2/2 \end{cases} \rightarrow \begin{array}{l} X = x \\ X = \lambda_1 - x \\ X = x - \lambda_1 \\ X = \lambda - x \end{array} \qquad (2)$$
$$if \;\; x \leq \lambda_1$$
$$R_j(z) = R - R_1 + \sqrt{R_1^2 - (\lambda_1/2 - X)^2}$$
$$if \;\; x > \lambda_1$$
$$R_j(z) = R - (A_1 + A_2) + R_2 + \sqrt{R_2^2 - (\lambda_2/2 - X)^2}$$

Where R is tool radius and the other parameters are shown in Figure 4.

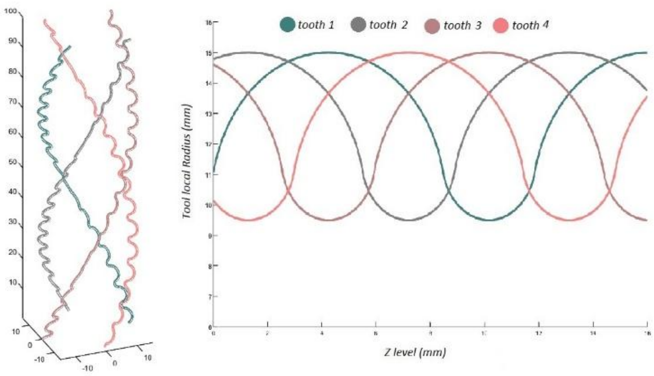


Figure 5. Schematic view of an end mill with the circular serration and Variation of local radius along tool axis

2.3 Trapezoidal Serration form

Another type of serration wave which is used in industry is trapezoidal serration. The wave shape and its parameters are shown in Figure 6.
The local radius of each tooth in each level in trapezoidal serration form can be calculated by the geometry relationships like other type of serrations.

The variation of the local radius and schematic view of the tool is demonstrated in the Figure 7.

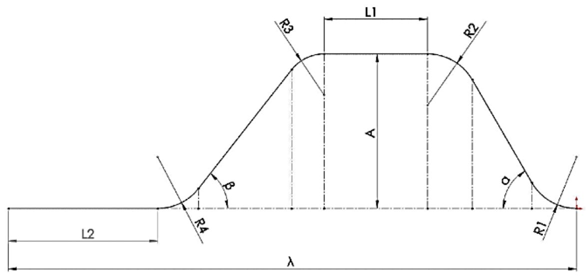


Figure 6 Trapezoidal serration wave parameters

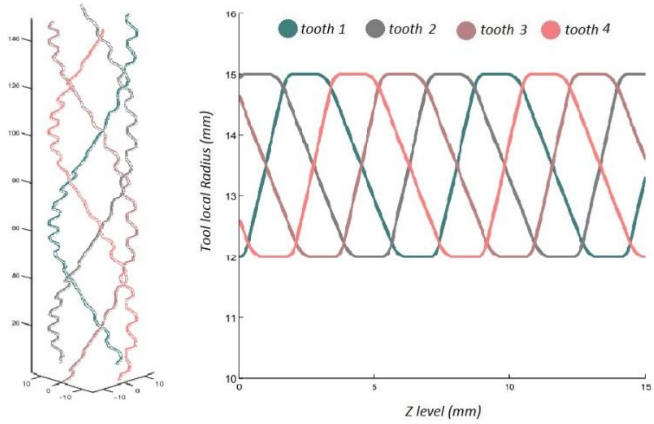


Figure 7. Schematic view of an end mill with the trapezoidal serration and variation of local radius along tool axis

2.1. Position of edge points

Angular position of element i on the tooth j in the height of z_i can be calculated as below:

$$\varphi_{ij} = \varphi + p_t(j) - \frac{\tan(\beta)}{R} z_i \qquad (3)$$

Where φ is the rotation angle of the end mill, β is the helix angle, R is the radius of the tool and p_t is the accumulative pitch angle of the j^{th} tooth which is defined as follows:

$$p_t(j) = \sum_{s=1}^{s=j} p(s) \qquad (4)$$

The position vector defines the place of point i, on the j^{th} edge at level z_i, in Cartesian coordinates. This Vector can be calculated by the following formulas:

$$P_{ij} = (R_j(z_i)\cos\phi_{ij})\vec{i} + (R_j(z_i)\sin\phi_{ij})\vec{j} + z_i\,\vec{k} \qquad (5)$$

2.2. Axial immersion angle

Axial immersion angle has the significant role on the force calculations. Immersion angle is the angle between the tool edge tangent vector and the unit vector which is directed toward edge along tool radius in x-y plane.
A vector between two end of the elements on the tool edge is a good approximation for tangent vector of the edge.

$$\vec{\tau}_{ij} = \vec{P}_{i+1j} - \vec{P}_{ij}$$
$$\vec{n}_{ij} = (\cos\phi_{ij})\vec{i} + (\sin\phi_{ij})\vec{j} \tag{6}$$
$$\kappa_{ij} = \cos^{-1}\left(\frac{\vec{\tau}_{ij} \cdot \vec{n}_{ij}}{|\vec{\tau}_{ij}||\vec{n}_{ij}|}\right)$$

2.3. Local rake and oblique angle

Because of the serration geometry of the tool, rake and oblique angles vary along teeth. And it is known that [2], the cutting coefficients are dependent on these angles so they have significant effect on cutting forces. Consequently, the cutting angles should be calculated for each tooth in each axial element.

Local rake and local oblique angles for each element on each tooth can be derived from geometrical relationships.

3. Force Model

For milling forces linear edge force model [9] is adopted. In order to obtain cutting forces, first, differential forces are calculated for each axial element at any rotational step in one full revolution.

$$\begin{aligned} dF_a(j,z) &= g(\varphi_j(z))\left[K_{ae} + K_{ac}h(j,z)\right]db \\ dF_r(j,z) &= g(\varphi_j(z))\left[K_{re} + K_{rc}h(j,z)\right]db \\ dF_t(j,z) &= g(\varphi_j(z))\left[K_{te} + K_{tc}h(j,z)\right]db \end{aligned} \tag{7}$$

Where $g(\varphi_j(z))$ is a step function. $g(\varphi j(z))$ is zero when the tooth is not in cut (φ_j is not between φ_{start} and φ_{exit}) and it is one when the tooth is in cut (φ_j is between φ_{start} and φ_{exit}). K factors are cutting and edge forces coefficients in different directions. db is defined by equation (8).

$$db = \frac{dz}{\sin(\kappa_{ij})} \tag{8}$$

And chip thicknesses are calculated by the equation (9).

$$\begin{aligned} & h_j(\phi_j, z) = \\ & \qquad \max\begin{Bmatrix} 0 \\ \min\left\{R_j(z) - R_m(z) + kf_t\sin(\phi_j)\right\} \end{Bmatrix} \\ & m = \begin{cases} k-j & if \quad k-j>0 \\ k-j+N_t & if \quad k-j\le 0 \end{cases} \\ & k = 1,2..,N_t \end{aligned} \tag{9}$$

By using differential forces in tool coordinates, the differential forces in x,y and z directions can be expressed as follows:

$$\begin{aligned} dF_x &= -dF_r\sin(\varphi_j)\sin(\kappa) \\ &\quad - dF_t\cos(\varphi_j) - dF_a\cos(\kappa)\sin(\varphi_j) \\ dF_y &= -dF_r\cos(\varphi_j)\sin(\kappa) \\ &\quad + dF_t\sin(\varphi_j) - dF_a\cos(\kappa)\cos(\varphi_j) \\ dF_z &= dF_r\cos(\kappa) - dF_a\sin(\kappa) \end{aligned} \tag{10}$$

Total forces in x,y and z directions in each angular increment can be calculated by the summation of the differential forces from all elements and teeth

$$\begin{aligned} F_x(\varphi) &= \sum_{z=0}^{a}\sum_{j=1}^{N_t} dF_x(z,j) \\ F_y(\varphi) &= \sum_{z=0}^{a}\sum_{j=1}^{N_t} dF_y(z,j) \\ F_z(\varphi) &= \sum_{z=0}^{a}\sum_{j=1}^{N_t} dF_z(z,j) \end{aligned} \tag{11}$$

4. Experimental Verification

In order to obtain the forces in milling process some experiments with serrated end mills was performed. These tests were carried out on the MAZAK 3-axis CNC machine and Al7075 was chosen as work-piece material. The end mills had 4 cutting teeth and their radius was 6mm. Also their rake and helix angles were 5° and 30° respectively. The parameters of the process and tool serration waves in 3 tests are shown in Table 1. Figure 8,Figure 9Figure 10 are showing the comparison of test and simulation results.

Table 1. Test Parameters

No.	Serration wave form	Serration parameters (mm)	Process parameters
1	Trapezoidal	L1=0.3, L2=0.2 A=0.5, α=β=45° R1=R2=R3=R4=0.2 Ps= [0° 270° 180° 90°]	a=15 mm b=3 mm f=0.1 mm/rev.tooth down milling
2	Sinusoidal	WA=1 WL=2 Ps= [0° 270° 180° 90°]	a=5 mm b=3 mm f=0.15 mm/rev.tooth down milling
3	Circular	R1=R2=0.5 A1=A2=0.6 Ps= [0° 270° 180° 90°]	a=15 mm b=3 mm f=0.1 mm/rev.tooth down milling

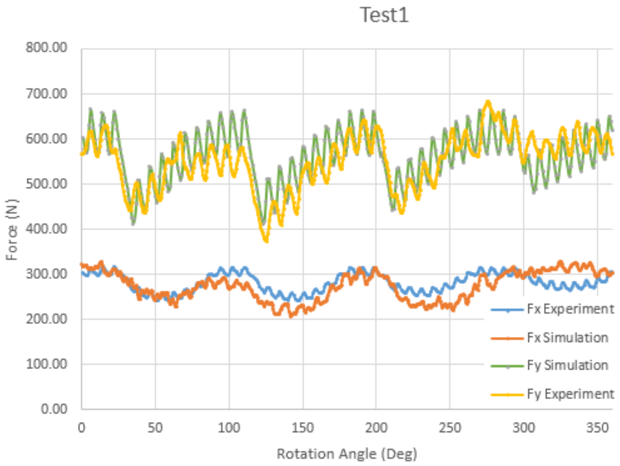


Figure 8. Test 1 Results

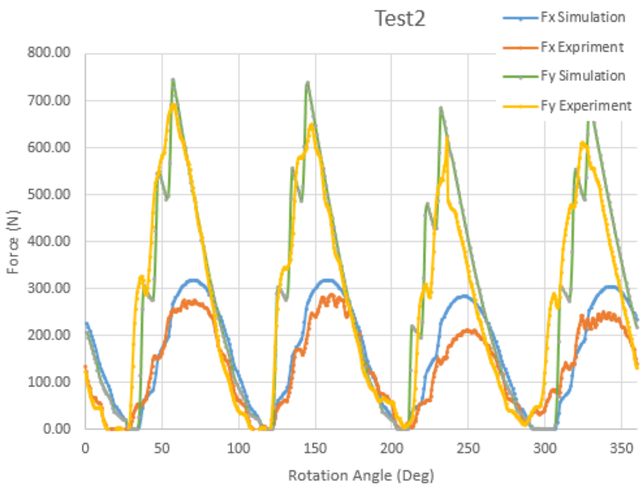


Figure 9. Test2 Results

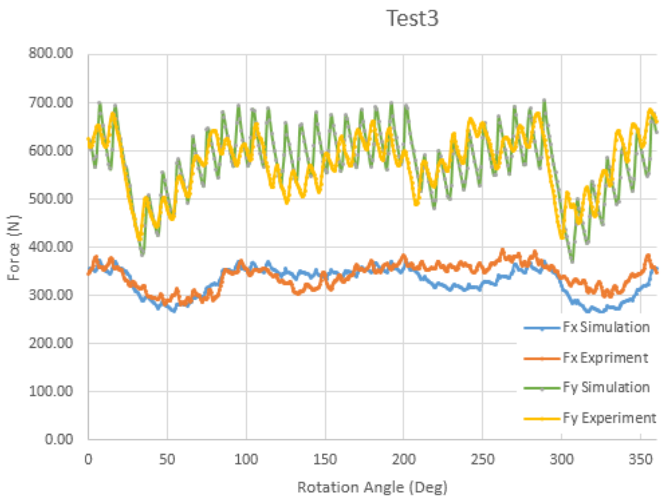


Figure 10. Test3 Results

As shown in the figures, experimental and simulation results are in good agreement.

5. Effect of serration parameters

The simulation results show that serration parameters have significant role on the milling forces. As a simple instance the effect of sinusoidal serration wave parameters on the maximum F_{xy} was investigated. In these sample simulations axial depth of cut, radial depth of cut and feed rates are chosen as 10mm, 5mm and 0.1mm/(rev.tooth) respectively. The end mill with sinusoidal serration has 10mm diameter and rotates in 1500rpm. The effect of the wave length in two different wave amplitude on the milling forces is shown in the Figure 11.

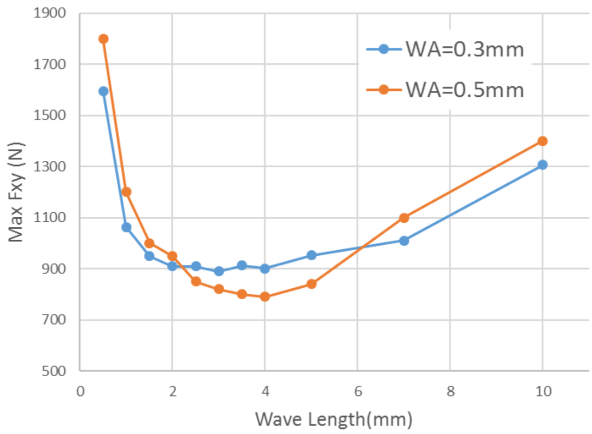


Figure 11. Maximum F_{xy} for different sinusoidal serration shapes

Figure 11 shows that F_{xy} changes between 1800N to 800N by using different serration parameters. This figure illustrates the importance of the proper design of serration parameters. In addition, it shows that parameters have no predictable effect on the maximum resultant force.

There are two ways to find the optimum design for the tool serration wave in different conditions. The optimum serration can be found by simulating all the possible conditions and find the best design by comparison of solutions. It is obvious this method is time consuming and it is not efficient. Another procedure is using evolutionary optimization algorithms which search the solution space in a much smart way and as result they find optimum solutions faster than first method.

6. Optimization of serration wave shape

In this section, serration wave shape is optimized by using genetic algorithm in order to reduces cutting forces. GA is a method for moving from one population of chromosomes to a new population by using a kind of natural selection together with the genetics–inspired operators of crossover and mutation. By using the selection operator, on the average, the fitter chromosomes produce more offspring than the less fit ones. Crossover exchanges subparts of two chromosomes and mutation randomly changes the values of some locations in the chromosome [5]. These operations result in new generations, more compatible with the problem conditions. This competition between chromosomes, overcome of dominant chromosomes (to be chosen by algorithm for next generation) and elimination of recessive chromosomes, i.e.

solutions far from target, is an efficient way to solve complex problems.

Problem is defined by tool and process parameters such as tool radius, feed rate, radial depth of cut, axial depth of cut etc. Moreover, the range of variation for each serration parameter is specified. After the definition of the problem, GA runs 3 times (it runs for three serration types). After finding the optimum serration parameters for each wave the algorithm chooses the best one as an optimum solution.

6.1. Genetic algorithm

The first step in solving any problem with GA is representation of solutions in the form of chromosomes. In this problem each solution is figured as a string and the string length is equal to the number of features it has. Therefore, the length of chromosomes for the sinusoidal, circular and trapezoidal serration is 6, 8 and 13 respectively.

The initial population can be produced by two ways: random procedure and systematic procedure. Obtained initial population with particular method decreases process time of algorithm but it may cause the algorithm to be trapped at local optimums. So in this study the initial population has been produced using random procedure.

The objective function can be defined as any weighted combination of the average or maximum forces in different directions (F_x, F_y, F_z, F_{xy}, F_{xz}, F_{yz}). Weights can be set according to desire of the problem.

In this investigation the fitness of each chromosome will be calculated as below:

$$f(u) = \exp\left[\frac{-\alpha \times F(\mathrm{u})}{Worst\ Cost}\right] \tag{12}$$

Where α is a scale factor, F(u) is the value of objective function for u^{th} chromosome and “worst cost” is objective function value of the worst chromosome.

Crossover is used in GA for information exchange between chromosomes. In the proposed algorithm, first the cut point is determined randomly on parents for creating two subsets. Then subsets places are exchanged between two parents. By this way two new offspring can be obtained.

Mutation function changes the value of the random number of gens in the chromosome. This function helps to search different areas of solution space and prevents being stuck in local optimums.

6.2. Optimization results

To demonstrate the efficiency of the proposed GA in this paper, the algorithm procedure was implemented in Matlab R2016a on a PC computer with Core i7 processor (4.01GHz) and 16GB of RAM. Three instances have been selected to evaluate the efficiency of the end mills which designed by proposed GA algorithm in comparison of normal end mills.

Al7075 was selected as work-piece material. The end mills had 4 cutting teeth and their radius was 6mm. Also their rake and helix angles were 5° and 30° respectively. The parameters of the processes and the optimum tool serration parameters for each process in three simulations are shown in Table 2.

Table 2. Optimized serrated end mills

No.	Serration wave form	Optimum serration parameters (mm)	Process parameters
1	Trapezoidal	L1=0.17, L2=0.25 A=0.28, α=37°, β=42° R1=0.11, R2=R4=0.07 R4=0.2 Ps= [321 57 152 234]	a=15 mm b=0.1 mm f=0.15 mm/rev.tooth down milling
2	Sinusoidal	WA=0.22 WL=2.7 Ps= [317 128 29 202]	a=5 mm b=3 mm f=0.15 mm/rev.tooth down milling
3	Circular	R1=R2=0.5 A1=A2=0.6 Ps= [0° 270° 180° 90°]	a=15 mm b=3 mm f=0.1 mm/rev.tooth down milling

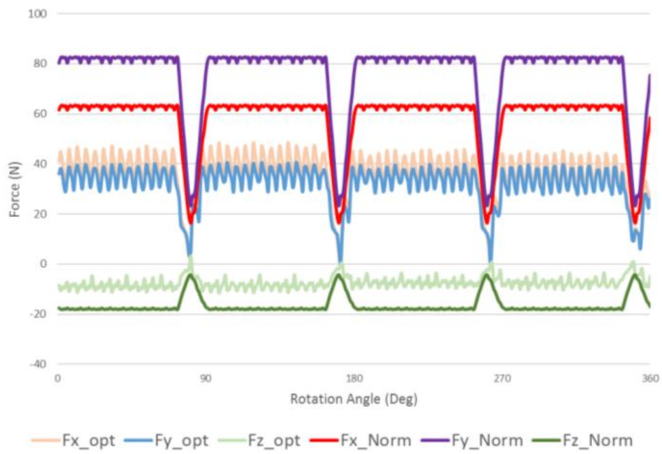


Figure 12. Force Simulation for Tool1 vs normal end mill

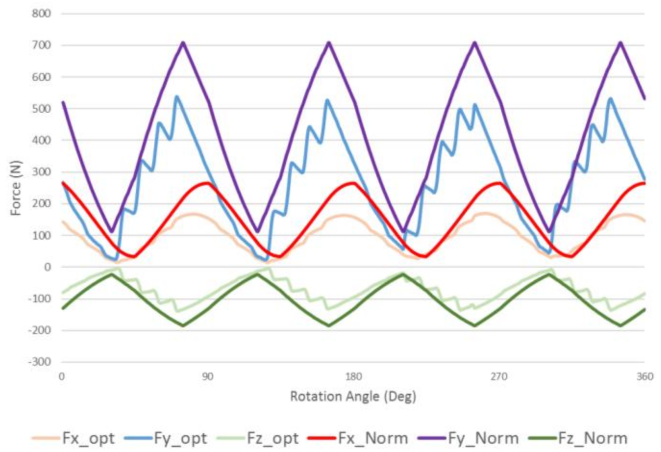


Figure 13. Force Simulation for Tool2 and normal end mill

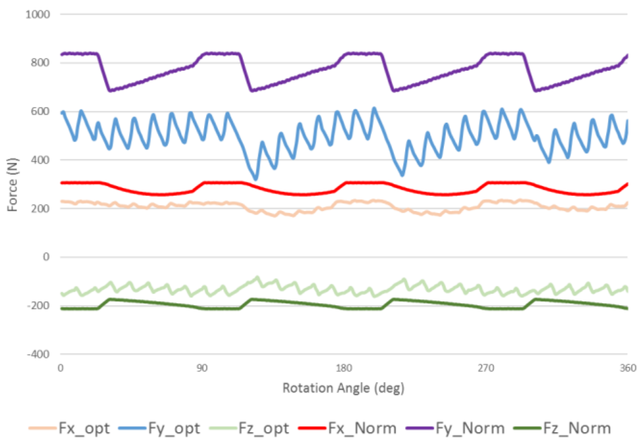


Figure 14. Force Simulation for Tool3 and normal end mill

7. Conclusion

In this study, geometry of serrated end mills was defined and mechanics of milling with these tools were investigated. Milling forces which were obtained from the proposed model was verified with experimental results and it was shown that there is good agreement between simulation and experimental results. Moreover, Genetic Algorithm was proposed for design of optimum serrated end mills in terms of milling forces. Efficiency of proposed approach was evaluated by solving some problems. The comparison between responses achieved in this study and available normal end mills, demonstrates the effectiveness of this algorithm.

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