Study on the Cutting Efficiency of High-Speed Band Saw Blade by Taylor Tool Life and Fractal Equations

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Abstract. The study proposed the chip formation steady-state model and cutting efficiency model for multi-cutters by Taylor tool life and fractal equation according to uniform chip thickness in high-speed band sawing process. Furthermore, a kind of new hook-tooth can be successfully applied on continuously uniformed chip formation in order to raise the production precision. The study developed MDOF cutting dynamics, which can be applied on multi-cutting process by Taylor tool life and fractal equations. Factors of affecting band-sawing included the cutting force, the cutting geometry, the cutting heat, the local stress-strain and the chip thickness formation uniformity. These factors had an important influence on tool wear, surface roughness, production precision and cutting efficiency in high-speed sawing process. The simulated results shown that, the wear resistance property is better at coating TiN 0.6 μm . In high-speed cutting process, the cutting improvement rate can be increased at least 13%. While the hook-tooth cutting speed achieved 120 m/min, comparing with non-coating cutting tooth, coating 0.6 μm coating-layer can make the temperature decreased, obviously.

1 Introduction

Factors of affecting band-sawing include cutting force, cutting geometry, cutting heat, local stress-strain and chip thickness formation uniformity. These factors have an important influence on tool wear, surface roughness, production precision and cutting efficiency in high-speed sawing process. It is effective to improve machining quality, raise cutting efficiency and reduce the cost by controlling these factors. The study proposed cutting factors of tool geometry in band-sawing process, simulated and improved the machining characteristics and investigated the effects of vary kinds of cutters geometry in sawing process. By using the optimal process parameters, including coating factors, cutting velocity, tool geometry, tool material and workpiece material to improve cutting temperature, cutting resistance and the production qualities will achieve a better standard.

1.1 Paper Review

Band-saw types can be distinguished from the straight-cutters, wave-cutters, sinusoidal-cutters, circle-cutters and wire-saw depended on saw-blade geometry, and machining mechanism applied on multi-points cutting. According to the band-saw with different kinds of saw-blade, it can be processing on metal, wood, plastic material and even in semi-conductive chip. Earlier studies, there were a lot of papers investigated about band-sawing process. According to the studies, the cutter design has greater effects on cutting process, and then, it will cause tool wear fast and bad surface roughness,

especially for the tool life decreasing. Ko and Kim [1] analyzed saw-blade geometry and mechanistic cutting force prediction agreed well with experimental trends. Andersson [2-4] used the FEM demonstrated that, the maximum stress had decreasing with cutter radius increasing. The kind of tool geometry variation caused cutting force variation along feed direction and linear increasing with undeformed chip thickness. Marusich [5] et. al simulated the cutting process under residual stress with considering heat performance, tool geometry and machining parameters on workpiece. They found the relations of stress, cutting velocity and chip load. Xu and Yu [6] investigated sawing performance of diamond with alloy coatings, and the coating can raise the TRS performance. Okai [7] et. al used saw-blade analyzed to investigate the effects of cutting velocity and cutting force, however, the cutting tool caused wear because of cutting heat and local stress concentrated. Buyuksehir [8] investigated specific wear ratio and obtained specific energy under up-cutting modes, and determined the optimal performance between process parameters, cutting depth and workpiece moved velocity. Besides, wire-saw is another important machining application for natural stones and architecture. Wu [9] et. al studied multi-points by chip fractal geometry and hack-sawing mechanism, and predicted cutting force, boundary conditions, undeform cutting areas and specific energy trends, successfully. Thaler [10] et. al studied the stability diagrams and chatter avoidance in horizontal band sawing, and the experimental results the analysis of chatter avoidance is better than unstable cutting force signals. To raise the cutting efficiency and cutting velocity, the cutting stratray is to reduce chatter occurred. Patten [12] et. al used AdvanEdge to establish cutting

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model, such as feed, edge radius, cutting depth 10 micrometer and cutting velocity 1~300 m/min. They found the toughness shearing occurred in high-speed sawing process. Usui [13] et. al proposed a kind of finite element model to calculate chip geometry, cutting force and surface hardening by applying Lagrangian method to predict AISI 4130 chip breaking. Grzesik [14] et. al used FEM the orthogonal cutting process by coating tool and uncoating tool with adding TiC and Al₂O₃ deposited on P20 carbo-material. Fang [15] et. al proposed the heat-elastic-plastic coupling model to simulate 3 dimensional FEM, and the results demonstrated the stress concentration on tool-edge section and the higher stress focus on the main deformation zone. Usui [16] studied 3D FEM, including adaptive meshing, heat-mechanical coupling, strain rate and high temperature deformation for tool. Stephenson [17] et. al proposed 3-D FEM for drilling model, including adaptive meshing, heat-mechanical coupling effect, strain rate and high temperature deformation for tool. Mohammadpour [18] et. al observed the residual stress influence of cutting velocity and feed rate in orthogonal cutting process, and the results the chip formation and stress distribution can be successfully predicted by MSC. Superform. Huang and Yang [19] indicted the energy reduced from the cutting heat in high-speed cutting process, resulted in the non-uniform heat distribution on workpiece. Fractal is a kind of mathematical tool to solve the transient problems by Mandelbrot [20], who proposed W-M fractal function in order to simplified Weierstrass equation to simulate roughness profile by topothesy and random phase.

2. Theoretical Modelling

The study developed MDOF cutting dynamics, which can be applied on multi-cutting process by Taylor tool life and fractal equations. The maximum material removal rate (MMR) and chip thickness uniformity were the objective functions, which simulated on S45C in order to find out the optimal geometric and process parameters in multi-points sawing process.

2.1 MDOF Cutting Dynamics

From Fig. 1 (a)-(e), the MDOF cutting dynamics can be established by steady-state chip formation without self-excited vibration. In brief, the governing equation for MDOF can be written as Eq. (1)

$$[M][\ddot{x}] + [c][\dot{x}] + [k][x] = [0] \quad (1)$$

Hence, Eq.(2) to Eq.(4) can be obtained as generalized matrix by conservation of energy.

$$[M] = \begin{bmatrix} m_1 & 0 & 0 & \cdots & 0 \\ 0 & m_2 & 0 & \cdots & 0 \\ 0 & 0 & m_3 & \cdots & 0 \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & 0 & \cdots & m_n \end{bmatrix} \quad (2)$$

$$[c] = \begin{bmatrix} c_1 & c_1 + c_2 & 0 & \cdots & 0 \\ c_1 + c_2 & c_2 & c_2 + c_3 & \cdots & 0 \\ 0 & c_2 + c_3 & c_3 & \cdots & 0 \\ \vdots & \vdots & \vdots & \cdots & c_{n-1} + c_n \\ 0 & 0 & 0 & c_{n-1} + c_n & c_n \end{bmatrix} \quad (3)$$

$$[k] = \begin{bmatrix} k_1 & k_1 + k_2 & 0 & \cdots & 0 \\ k_1 + k_2 & k_2 & k_2 + k_3 & \cdots & 0 \\ 0 & k_2 + k_3 & k_3 & \cdots & 0 \\ \vdots & \vdots & \vdots & \cdots & k_{n-1} + k_n \\ 0 & 0 & 0 & k_{n-1} + k_n & k_n \end{bmatrix} \quad (4)$$

For furthermore, take Laplace Transform, and assumed $\{x\} = \{\bar{x}\} e^{st}$ subinto Eq.(1)

$$s^2 [M][\bar{x}] + s [c][\bar{x}] + [k][\bar{x}] = \{0\} \quad (5)$$

Through reduced order, assumed

$\{\hat{x}\} = s \{\bar{x}\}$ subinto Eq.(5), Eq.(6) can be obtained.

$$\begin{bmatrix} \bar{x} \\ \hat{x} \end{bmatrix} s \begin{bmatrix} \bar{x} \\ \hat{x} \end{bmatrix} = \begin{bmatrix} 0 & I \\ -[M]^{-1}[k] & -[M]^{-1}[c] \end{bmatrix} \begin{bmatrix} \bar{x} \\ \hat{x} \end{bmatrix} \quad (6)$$

To solve the eigenvalues and eigenvectors from 2n set, $\{S_k\}_{n*1}$ and $\{S_n^*\}_{n*1}$, where $S_k = -\delta_k + j\omega k$, $s_k = -\delta_k - j\omega k$

The generalized displacement of cutter edge can be written as Eq.(7)

$$\begin{aligned} \{X_k(t)\} &= c_{1k} e^{S_k t} \{X_k\} + c_{2k} e^{S_k^* t} \{X_k^*\} \\ &= e^{-\delta_k t} \left(e^{j\omega k t} c_{1k} \{X_k\} + e^{-j\omega k t} \{X_k^*\} \right) \\ &= \{XX\}_k e^{-\delta_k t} \cos(\omega k t - \theta_k) \end{aligned} \quad (7)$$

Where $\{XX\}_k = \sqrt{(c_{1k} X_k + c_{2k} X_k^*)^2 - (c_{1k} X_k - c_{2k} X_k^*)^2}$;

$$\theta_k = a \tan \left(\frac{j(c_{1k} X_k - c_{2k} X_k^*)}{c_{1k} X_k + c_{2k} X_k^*} \right) \quad (8)$$

Hence, Eq.(7) can be rewritten as Eq.(9)

$$\{X(t)\} = \sum_{k=1}^n \{XX\}_k e^{-\delta_k t} \cos(\omega k t - \theta_k) \quad (9)$$

For a tiny displacement dx at differential-cutter, the tiny feed df will be occurred at the same time t , hence, Eq.(10) can be derived.

$$\gamma = \tan^{-1} \left(\frac{dx}{df} \right) \quad (10)$$

If the chip formation is steady-state, the γ is usually constant, called differential-cutter angle. For two dimensional orthogonal cutting, Eq.(11) can be expressed MDOF cutting from every single unit cutter.

$$\int_0^l \{X(t)\} dx = \int_0^h \tan(\gamma) df \quad (11)$$

Where l means the cutting length from the workpiece, and h means the average cutting depth. For furthermore, the transient chip load for every single cutters can be derived from feed $df(t)$, cutting width b and cutting overlap ratio α from chip fractal geometry. Average specific energy K_t can be obtained through unit cutting areas of multi-cutters as Eq.(12)-Eq.(15)

$$K_t = \frac{W}{\Delta V} \quad (12)$$

For single cutters,

$$W = K_t V_s = K_t L A_s \quad (13)$$

For multi-cutters,

$$W = K_t V = K_t \sum_{i=1}^n A_i l_i \quad (14)$$

The study denotes average specific energy K_t and average cutting force for multi-cutters,

$$\bar{F} = \bar{K}_t \left(\sum_{i=1}^n a_i \right) \quad (15)$$

2.2 Fractal Differential Equation

In order to obtain chip fractal self-similarity, the cutting tool can be expressed as sinusoidal-wave through one-dimensional projection and become 84 cutter topologies. According to sinusoidal multi-cutters, the cutters interference ratio of cutter arrangement can be written as Eq. (16).

$$\alpha_{n+1} = 1 - \frac{\lambda}{n \cdot b} (\tan \theta_{n+1} - \tan \theta_n) \quad (16)$$

Where α_{n+1} means $(n+1)^{th}$ cutter; λ denotes the length of unit wave; n means cutter number of period; b means cutter width; θ_{n+1} means the banding angle of unit cutter. The equivalent depth under cutter interference in cutting process can be demonstrated as Eq.(2) and Fig.1, called fractal- algebraic operators.

$$d_{i,max} = d_1^* \left(\frac{\alpha_i}{1-\alpha_i} \right)^{n-1} + (1-\alpha_i)(d_{i-1} - d_{i-2}) + d_1^* \quad (17)$$

Where d_1^* means the initial cutting depth according to experimental results; d_i means the transient cutting depth for i^{th} cutter of total working cutters. To consider the chip load of the equivalent depth and cutting width in two-dimension, the chip load can be presented as Eq. (17) without energy dissipated.

$$\begin{aligned} P_i &= A_i \\ &= b_i \times d_i \\ &= b_i \left[d_1^* \left(\frac{\alpha_i}{1-\alpha_i} \right)^{n-1} + (1-\alpha_i)(d_{i-1} - d_{i-2}) + d_1^* \right] \\ &= (1-\alpha_i) b_i \left[d_1^* \left(\frac{\alpha_i}{1-\alpha_i} \right)^{n-1} + (1-\alpha_i)(d_{i-1} - d_{i-2}) + d_1^* \right] \end{aligned} \quad (18)$$

A_i means the chip load under geometry interference, and the shape has strictly fractal self-similarity It is key point to determine the boundary orders in order to obtain exact convolution function. Due to geometric characteristics, Eq. (18) can be shown as chip-load geometric factors of cutting process, called chip load

function of sinusoidal multi-cutters. Eq. (18) can be also rewritten as a functional expression as Eq. (19)

$$P(d_i, \alpha_i, b, n, \theta_i) = (1-\alpha_i) b_i \left[d_1^* \left(\frac{\alpha_i}{1-\alpha_i} \right)^{n-1} + (1-\alpha_i)(d_{i-1} - d_{i-2}) + d_1^* \right] \quad (19)$$

From Eq. (19), $\tan \theta = R \sin \left(i \times \frac{2\pi}{n} \right) / t_p$; R means amplitude of sinusoidal-set cutters; t_p means cutter pitch

2.3 Taylor's Tool Life and Cutting Efficiency Model

The traditional Taylor's tool life can be demonstrated as Eq. (20)

$$VT^n = C \quad (20)$$

Where $n = \frac{\log \left(\frac{C}{V} \right)}{\log T}$, V means cutting velocity and T

denotes the tool life, n means exponent.

Extend Eq. (20), the generalized form can be rewritten as Eq. (21) for more process parameters

$$[F_c]^f [P]^m [N]^d [f]^q V [T]^n = C_1 \quad (21)$$

Where f means the cutting force exponent; m means the exponent for the cutting numbers of workpieces; d means the exponent of coating layer thickness; q means the exponent for feed.

Simultaneously, the raising cutting efficiency model for multi-cutters can be derived from Taylor's Tool life equation as Eq. (22)

$$E = \eta (\%) \cdot e^{-\eta \cdot 10} \quad (22)$$

Where E means the cutting efficiency for multi-cutters, and η means the percentage of single-cutter cutting efficiency. From the simulation of single-cutter, it can be extended to the multi-cutters cutting efficiency obtained by Eq. (22)

In order to obtain the temperature variation of cutter edge and chip surface, where the Johnson-Cook equation used as Eq. (23), it assumed the temperature conduction between tool and workpiece. The study doesn't be considered cutting temperature conducting into the air.

$$\sigma_{eq} = (A + B \varepsilon_n) \left(1 + C \ln \left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right) \left(1 - \left(\frac{T - T_{room}}{T_m - T_{room}} \right)^m \right) \quad (23)$$

Where T_m means the melting point temperature; T_{room} means the environmental temperature; T means the workpiece temperature; A means the yielding stress; B means the strain factor; n means the strain coefficient; m means the temperature coefficient; ε means the plastic strain ratio; ε_0 means the stain ratio

Cutting tool suffered loading will be occurred stress and strain, result in the body deformation. The strain can be distinguished from normal strain and shear strain. The physical meanings are length deformation and the variation of angle. If the model considers shear strain without normal strain, the Eq. (24) and Eq. (25) can be expressed.

$$\varepsilon_{xx} = \frac{x' - x}{x} = \frac{\sqrt{x^2 + \delta_y^2} - x}{x} \cong \frac{x - x}{x} = 0 \quad (24)$$

$$\gamma_{xy} = \theta_1 + \theta_2 \cong \tan \theta_1 + \tan \theta_2 = \frac{\delta_x}{x} + \frac{\delta_y}{y} \quad (25)$$

The simulation processes the band-saw orthogonal cutting by Lagrangian finite element method and numerical analysis.

3. Results and Discussion

The study proposed the chip formation steady-state model and cutting efficiency model for multi-cutters by Taylor tool life and fractal equation according to uniform chip thickness in high-speed band sawing process as **Fig. (a)-(d)**. The uniformity of the study has two, one is the chip thickness uniformity, and the other is cutting temperature uniformity. Furthermore, a kind of new hook-tooth can be successfully applied on continuously uniformed chip formation in order to raise the production precision. **Fig.1 (b)** demonstrates a kind of hook-tooth design with coating TiN 0.2 ~0.6 μm and uncoating simulation. Initial chip formation and mesh has good uniformity from **Fig. 1 (d)**. H-adaptive model can cause the fine mesh to the cutting precision raising.

Fig.1. (a) Multi-degree-of-freedom cutting modelling; (b) chip formation for multi-cutters; (c) mathematical model for single cutter; (d) initial chip formation and mesh; (e)

steady-state chip formation without considering self-excited vibration

3.1 Hook-Tooth Design and Simulated Parameters

Hook-tooth design can cause the higher shear strain rate to remove the chip, and furthermore, the tool obtained the smaller cutting temperature in order to extend the tool life. **Fig. 2** and **Table 1** demonstrated that, the cutting temperature for the relations of variations of cutting velocity from 40 m/min to 80 m/min and feed rate from 45 cm^2/min to 65 cm^2/min (at the middle section 1.51~3.00 mm of cutting length).

Table 1. Simulated Parameters

Workpiece Parameters						
Material	S45C					
Hight (mm)	0.35					
Width (mm)	4.5					
Process Parameters						
Chip Load (mm)	0.05					
Band Saw Thickness (mm)	1					
Cutting Length (mm)	5					
Cutting Velocity (m/min)	40	50	60	80	120	
Feed Rate (mm/s)	0.58		0.71		0.83	
Coating Parameters						
Layer	1					
Coating Material	TiN					
Coating Layer Thickness (µm)	uncoating		0.2		0.6

Fig.2. The cutting temperature for the relations of variations of cutting velocity from 40 m/min to 80 m/min and feed rate from 45 cm^2/min to 65 cm^2/min (at the middle section 1.51~3.00 mm of cutting length)

The study investigated the effect of cutting velocity from lower velocity 40 m/min to high-speed 120 m/min. In ultra-speed sawing process, the WC tool-edge will achieve transient higher temperature 400 deg. C. In order to solve the problem under high temperature, the edge coating for adaptive coating-layer range is very important. TiN coating is an anti-wear layer to reduce the cutting temperature raising. Besides, cutting efficiency model from **Eq.(22)** can predict the steady-state chip formation or unsteady-state chip formation form single-cutter to multi-cutters. Obviously, **(a)-(c)** mean the single cutter ($V=60\text{m/min}$), the temperature on coating-layer 0.2~0.6 is lower than single cutter of uncoating-layer; **(d)-(f)** mean the single cutter ($V=120\text{m/min}$); the temperature on coating-layer 0.2~0.6

is lower than single cutter of uncoating-layer from **Fig. 3- Fig. 5**.

Fig.3. Temperature at section (Local 1/3 length 0.00 mm~1.50 mm); (a)-(c): single cutter ($V=60\text{m/min}$), the temperature on coating-layer $0.2\sim0.6\ \mu\text{m}$ is lower than single cutter of uncoating-layer; (d)-(f): single cutter ($V=120\text{m/min}$); the temperature on coating-layer $0.2\sim0.6\ \mu\text{m}$ is lower than single cutter of uncoating-layer

Fig.4. Temperature at section (Local 2/3 length 1.51mm~3.00mm); (a)-(c): single cutter ($V=60\text{m/min}$), the temperature with cutting length increasing on coating-layer $0.2\sim0.6\ \mu\text{m}$ is lower than single cutter of uncoating-layer; (d)-(f): single cutter ($V=120\text{m/min}$); the temperature with cutting length increasing on coating-layer $0.2\sim0.6\ \mu\text{m}$ is obviously lower than single cutter of uncoating-layer

Fig.5. Temperature at section (Local 3/3 length 3.01mm~4.50mm); (a)-(c): single cutter ($V=60\text{m/min}$), the temperature with cutting length increasing on coating-layer $0.2\sim0.6\ \mu\text{m}$ is lower than single cutter of uncoating-layer; (d)-(f): single cutter ($V=120\text{m/min}$); the temperature with cutting length increasing on coating-

layer $0.2\sim0.6\ \mu\text{m}$ is obviously lower than single cutter of uncoating-layer; temperature on cutter edge has decreasing with coating-layer increasing, and benefits for tool life.

Fig.6 (a) $V=60\text{m/min}$ for single cutter; (b) $V=120\text{m/min}$ for single cutter is lower down than uncoating cutter ($0.6\ \mu\text{m}$)

Fig.7. (a)-(b) for single cutter on $V=60$ m/min (coating $0.2 \sim 0.6 \mu\text{m}$ is better than uncoating); (c)-(d) single cutter on $V=120$ m/min (coating $0.6 \mu\text{m}$), no variation for average force

In high-speed sawing process, the cutting temperatures at different locations are different due to the contact time of tool on workpiece. The relations of cutting velocity and cutting temperature from $V=60$ m/min to $v=80$ m/min have the same trends, summarized as **Fig. 6**. **Fig. 6 (a)** expressed the variation of the average cutting temperature at three sections of cutting length (420 Deg. C to 470 Deg. C); **(b)** means the variation of the average cutting temperature at three sections of cutting length (510 Deg. C to 560 Deg. C). Through cutting efficiency model, the cutting efficiency can be improved at least 13% by coating TiN layer $0.6 \mu\text{m}$. The average cutting force for cutting velocity 60 m/min to 120 m/min has the same trends for three sections of cutting length, and the cutter with coating TiN has lower cutting force than one without coating TiN as **Fig. 7 (a)-(d)**.

To observe the simulation of stress-strain for multi-hook tooth design, **Fig.8** expressed the first cutter of new hook-tooth design obtain the uniform cutting stress. First cutter design can simultaneously add chip thickness uniformity and lower cutter edge stress, but flank wear still existed. Shear stress from von Mises will be increasing, and it can help chip break. The maximum shear stress 933 MPa distributed on tool-edge, reasonably. The stress X-X and stress Y-Y were under controlled as **Fig. 8**. **Fig.9** shown the second cutter of new hook-tooth design in order to obtain uniform cutting stress as (a) maximum principle stress; (b) von Mises stress; (c) stress Z-Z; (d) uniform chip formation. The analysis of von Mises can find the maximum stress on tool flank, which means the flank wear will be occurred in high-speed dynamics. Due to **Fig. 9 (d)**, the hook-

tooth design indeed produced the better uniform chip formation, continuously.

Fig. 8. First cutter of new hook-tooth design in order to obtain uniform cutting stress; (a) von Mises stress; (b) maximum shear stress; (c) stress X-X; (d) stress Y-Y

Fig.9. Second cutter of new hook-tooth design in order to obtain uniform cutting stress; (a) maximum principle stress; (b) von Mises stress; (c) stress Z-Z; (d) uniform chip formation

3.2 Vibration and Frequency Response in High-Speed Sawing Process

The mainly measured locations were on S45C first, middle and last sections, and the values were expressed as vibration energy RMS. The RMS increased with cutting velocity increasing. The acceleration gages No.3 and No.4 had larger vibration RMS, because the locations were on cut-out, where the stiffness was not enough strong. The middle section on S45C has larger vibration because of the longest cutting length. The experimental vibration trends agreed well with the simulated cutting force profile as **Fig. 10 (a)**, and the average cutting force distributed on 400 N $\sim$ 500 N. Through a new tooth design, the smooth frequency response can be achieved as **Fig. 10 (b)**.

Fig.10. (a) Two-dimensional cutting force for new hook-tooth has better uniformity; (b) smooth frequency response

The validation used the 4 acceleration gages to measure the vibration (**Fig. 12 –Fig. 13**) compared with the simulated vibration and frequency response (**Fig. 10–Fig. 11**) has nicely trends from the three sections on S45C. Experimental preparation as **Fig. 12** (a) the location for No.1 to No.4 acceleration gage and S45C for first, middle and last section ; (b) COSEN company C-320GNC ; (c) PCB352C22 acceleration gage (d) NI-9234 vibration sampling device.

Fig.11. (a) Simulation of new hook-tooth design in order to obtain uniform cutting stress; (b) Burr for cutting out and uniform temperature distribution on chip surface (c) second chip temperature uniformity and continuous chip formation;

Fig.12. Experimental measurement device; (a) the location for No.1 to No.4 acceleration gage and S45C for first, middle and last section ; (b) COSEN company C-320GNC band-saw machine ; (c) PCB352C22 acceleration gage (d) NI-9234 vibration sampling device;

Fig.13. Vibration RMS on S45C first, middle and last section; the experimental results compared with the cutting force profile (Fig. 10 (a)) has the same trends from first, middle and last section on S45C

3.3 Chip Thickness Uniformity and Chip Temperature Uniformity

Simulation of new hook-tooth design can achieve chip thickness uniformity and chip temperature uniformity, simultaneously. To observe from Fig. 11, chip shape is an important feature. The chip formation from first cutter was nicely uniform and continuous. While the tool cutting out, the burr will be occurred on S45C. The chip surface temperature was about 500 deg.C, and the advantages of hook-tooth included that,

1. Good Surface Roughness
2. Good Cutting Force Distribution
3. Nice Chip Formation in High-Speed Sawing Process

Fig.14 The author Prof. Sung-Hua Wu stood around the COSEN Band-Saw Machine for MOST plan

The study can simulated the residual temperature about 256 deg.C on S45C. From the second cutter, it can occur the second chip temperature uniformity and continuous chip formation. The tooth design and coating under process parameters in high-speed sawing can be achieved the COSEN plan propurse (**Fig. 14**). By cutting mechanism adjusting, the MMR will be raising and tooth-bite improvement for future work.

4. Conclusions

The finding results in the study has been summarized as follows,

1. The study proposed the chip formation steady-state model and cutting efficiency model for multi-cutters by Taylor tool life and fractal equation according to uniform chip thickness in high-speed band sawing process.
2. The simulation successfully processed the band-saw orthogonal cutting by Lagrangian finite element method and numerical analysis.

3. Through cutting efficiency model, the cutting efficiency can be improved at least 13% by coating TiN layer 0.6 . The average cutting force for cutting velocity 60 m/min to 120 m/min has the same trends for three sections of cutting length, and the cutter with coating TiN has lower cutting force than one without coating TiN.
4. The study can simulated the residual temperature about 256 deg.C on S45C. From the second cutter, it can occur the second chip temperature uniformity and continuous chip formation.
5. The tooth design and coating under process parameters in high-speed sawing can be achieved the COSEN plan propurse.
6. First cutter design can simultaneously add chip thickness uniformity and lower cutter edge stress, but flank wear still existed. The maximum shear stress 933 MPa distributed on tool-edge, reasonably. The stress X-X and stress Y-Y were under controlled
7. If the chip formation is steady-state, the differential-cutter angle is usually constant.
8. For two dimensional orthogonal cutting, the MDOF cutting dynamics has been established on the study. In additions, the tool life equation can effectively predict the cutting performance of the band saw in order to improve the process efficiency and served as the reference of actual machining process.
9. While the hook- tooth cutting speed achieved 60 m/min, comparing with non-coating cutting tooth, coating 0.2~0.6 μ m was the highest temperature decreased obviously and the cutting force of hook-tooth also decreased.
10. The research put forward the cutting factors of the geometric structure of the band saw cutter, simulated and improved the processing characteristics during the cutting process, the impact of different cutting types by taking advantages of different process parameters, such as coating parameters, cutting speed and cutting feed.

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