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NUMERICAL STUDY OF EFFECT OF FLANK WEAR ON HEAT TRANSFER ABILITY IN HIGH-SPEED ULTRASONIC VIBRATION CUTTING INTERFACES

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Abstract

High-speed ultrasonic vibration cutting shown great advantages by cutting temperature reduction due to periodic opened cutting interfaces for direct heat convection with coolants. To figure out accurate heat transfer ability, a 2-dimensional simplified model was developed and computational fluid dynamics (CFD) was used to calculate heat flux and Nusselt number. Three flank wear lengths for initial, initial-stable transition and stable stages were chosen and comparisons made between CFD results and wear progresses indicated that heat transfer ability demonstrated better performance during the stable wear stage at low cutting speed. As cutting speed increased the effect of ultrasonic vibration was weakened.

Keywords:

Heat Transfer, Flank Wear, High-speed Machining, Ultrasonic Vibration Cutting, CFD simulation

1 INTRODUCTION

High-speed ultrasonic vibration cutting (HUVC) has been proved to be efficiently machining Ti and Ni alloys due to the advantages of huge cutting temperature reduction [Zhang 2022a]. The periodic opened cutting interfaces according to the vibration frequency was thought to be the core factor which in one hand could reduce the cutting force and in the other hand let the coolant penetrate into the cutting interfaces, and thus resulting direct heat convection between the coolant and heat sources [Zhang 2022b]. In this regard, unlike the traditional ultrasonic vibration cutting which had a critical cutting speed [Yang 2020], HUVC could obtain both the advantages of ultrasonic vibration cutting and high-speed machining [Sui 2017]. In the latest research [Zhang 2023], computational fluid dynamics (CFD) has been used to describe the transient states within the cutting interfaces at a 20 kHz frequency. Results have been found that the unstable thermal boundary layer (U-TBL) resulted from the reversed flow caused by ultrasonic vibration was the reason for heat transfer enhancement. Both the heat flux and Nusselt Number which indicated the absolute heat transfer ability and heat convection ability were significantly enhanced. Therefore, the tool life of HUVC could be prolongated approximately 2 to 3 times when machining titanium alloys.

Even though the cooling mechanism of HUVC has been revealed from the coolant aspect, the built model was focused on the whole tool wear progress. However, as the tool wear progressed, the flank wear was a dynamic varying state which could be divided into initial, stable and severe wear stages. In order to furtherly figure out the accurate stage where the advantages of HUVC appeared and took the dominant role, the effect of flank wear on heat transfer ability should be investigated. Therefore, in this paper, based on the proposed simplified model of HUVC interfaces, simulations by CFD were conducted. Finally, heat flux and Nusselt Number of each wear value and inlet coolant velocity were calculated, respectively. The transient temperature and synergy angle variations were also demonstrated accordingly.

2 MODELING OF HUVC INTERFACES

Illustrated in Fig.1a, during HUVC process, once the separation condition proposed by [Sui 2017] was satisfied, the tool would have a periodic separation from the workpiece in the feed direction. Thus, the coolant could have a chance to penetrate into the opened cutting interfaces demonstrated in Fig.1b. In this regard, the cutting heat could be directly transferred by the convection effect between the coolant and heat sources. The opened cutting interfaces could be simplified into a 2-dimensional model for further analysis and the length of the model was defined as flank wear value *VB*.

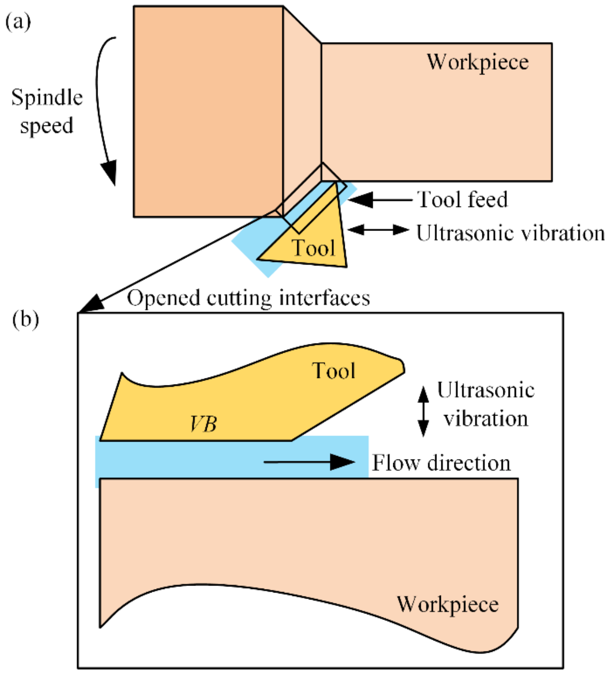

Fig. 1: Schematics of (a) HUVC process and (b) cutting interfaces.

Fig.2 shown the relationships between the tool wear duration and flank wear value of HUVC and conventional cutting (CC). It could be found the dash-dotted lines of three stages, i.e., initial, initial-stable transition and stable wear shared nearly same slopes. In this regard, the tool wear progress of CC had a nearly same wear speed until reaching the tool fail value. However, during the HUVC process, it could be found the dashed lines of stable wear stage had a larger slope than those of both the initial-stable transition and initial stages. When flank wear value was in the range of 0.15-0.25 mm, the cutting duration of HUVC was about 90 min while that of CC was only 25 min. The advantages of HUVC were shown when the tool wear went into the stable stages in which the length of the cutting interfaces defined in Fig.1b was the key factor that influenced the final tool performance.

3 CFD SET UP

A 2-dimensional simplified model of cutting interfaces was demonstrated in Fig.3. The variable of cutting interfaces length was chosen as 0.05, 0.15 and 0.25 mm to represent the initial, initial-stable transition, stable tool wear (VB) stages, respectively (Figs.3a, b, c). The up wall represented the ultrasonic vibration tool flank wear land was defined as a vibration wall by using dynamic mesh (Layering) while the bottom wall represented workpiece surface was defined as a fixed wall. The left wall was defined as a velocity-inlet where the velocity could be regarded as the workpiece rotary speed according to the flood penetration style in [Zhang 2023]. The right wall was defined as a pressure-outlet where the relative pressure could be defined as zero to describe the environment condition. Inlet coolant flow velocity to the left wall was defined as 1, 5 and 10 m/s to represent the cutting speed of 60, 300 and 600 m/min, respectively. It could cover the range from low to high cutting speed. In addition, the fixed wall temperature of 800 Celsius was defined onto both the up and bottom walls to describe the transient peak cutting temperature according to [Zoya 2000]. The sizes of mesh grids were 0.5 μm length and 0.1 μm width per one node.

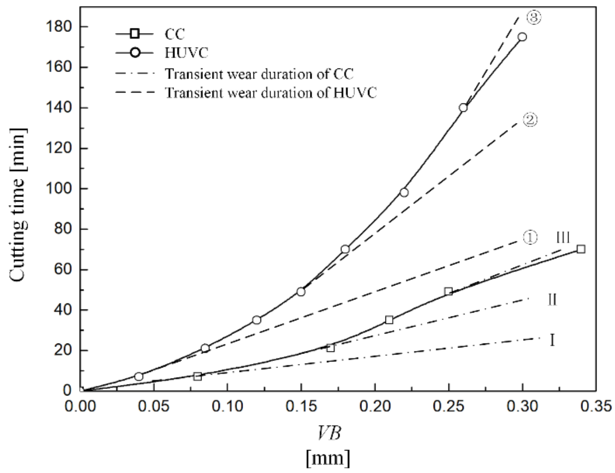

Fig. 2: Tool wear progress modified from Lu 2020.

The ultrasonic vibration parameters were set as 20 000 Hz frequency and 20 μm peak-valley amplitude. 1 μm gap was remained to represent the closed cutting interfaces when taking both the surface roughness and CFD continuity into considerations. Duty cycle was set as 0.5. In this regard, the width ranged from 1 to 11 μm during one vibration cycle.

According to [Zhang 2023]. the fluent could be treated as continuous flow which meant Navier-Stokes equation could be used. And thus *k-ε* SST method was applied to characterize the fluent state in transient issue section.

The calculations were conducted in successive 5 vibration periods and the data of 20 uniform moments during the last one vibration period were saved and analyzed. Heat flux could be given according to [Chen 2008] as follows:

$$q = \rho c_{\mathrm{p}} \int_0^{\delta} (\vec{U} \cdot gradT)\mathrm{d}y = \rho c_{\mathrm{p}} \int_0^{\delta} |\vec{U}||gradT| \cos\theta \,\mathrm{d}y \quad (1)$$

where ρ, c_{p}, δ, $\vec{U}$, T and θ were fluent density, heat capacity, boundary layer thickness, fluent velocity vector, temperature and synergy angle, respectively.When taking the ultrasonic vibration duration into consideration, Formula (1) could be modified into the following style:

$$q_{\mathrm{w}} = \frac{\int_0^t q(t)\mathrm{d}t}{t} \quad (2)$$

where q_{w} could be used to evaluate the heat transfer ability while the heat convection degree could be calculated by Nusselt Number as follows according to [Zhang 2023]:

$$Nu = Re_x Pr \int_0^1 \left|\bar{\vec{U}}\right| |grad\bar{T}| \cos\theta \,\mathrm{d}\bar{y} \quad (3)$$

where Re_x, Pr, $\bar{U}$ and $\bar{T}$ were Reynold number, Prandtl number, dimensionless velocity vector and dimensionless temperature, respectively. The discussions in Section 4 were focused on the calculation results of Formulas (2) and (3).

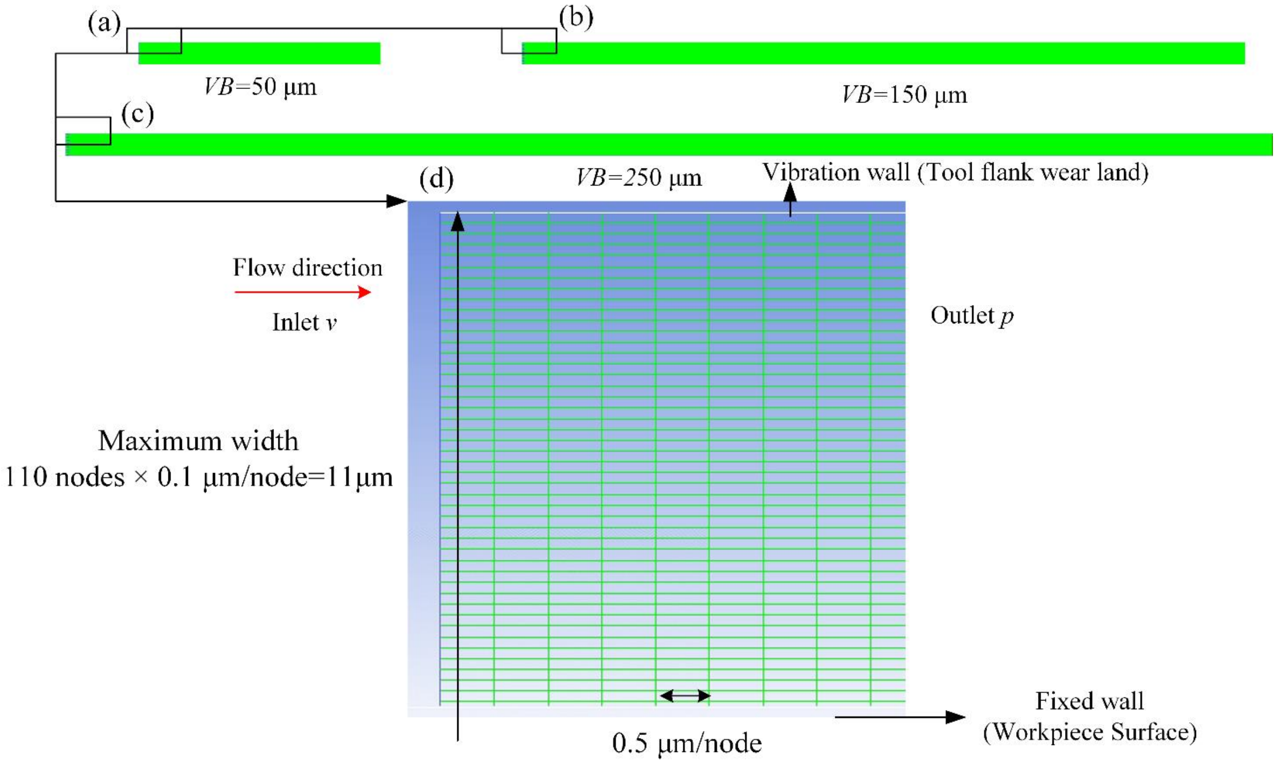

Fig. 3: Mesh grids of CFD set up. (a) VB=0.05 mm, (b) VB=0.15, (c) VB=0.25 and (d) detailed information

4 RESULTS AND DISCUSSIONS

4.1 Heat transfer ability

Heat flux and Nusselt number were shown in Fig.4a and 4b, respectively. From Fig.4a, it could be found that as the inlet coolant velocity increased, the heat flux would be enhanced according to Formula (1). As the inlet coolant velocity was increased from 1 to 5 m/s, the heat flux values of 0.05, 0.15, 0.2 and 0.25 mm flank wear were increased from 5521 to 7391, 15385 to 19394, 20019 to 25163 and 24419 to 30599 $J/m^2 \cdot s$, respectively. However, when the inlet coolant velocity was increased from 5 to 10 m/s, the improvement of heat flux for those values were 1488, 2443, 2733 and 3471 $J/m^2 \cdot s$ which were smaller than the previous values. The enhancement of heat flux was restrained when increasing the inlet coolant velocity. As the flank wear increased, the heat flux would also be increased approximately linearly. According to Formula (1) and Fig.3, it could be explained as the increase of heat transfer zone. Illustrated in Fig.4b, the Nusselt Number shown a reversed trend compared to that of heat flux when the inlet coolant velocity increased. In a low inlet coolant velocity, the effect of ultrasonic vibration took the dominant place and the long existence of U-TBL was the reason for the heat convection enhancement according to the analysis in [Zhang 2023]. Well field synergy effect between the flow velocity and temperature gradient led to this improvement in which the synergy angle was small according to Formula (1) [Liu 2009]. However, as the inlet coolant velocity increased, the U-TBL was restrained. In this regard, the heat convection was weakened.

Unlike the trend of heat flux versus flank wear, when the flank wear increased, the heat convection had a huge improvement. Taking 5 m/s as example, when VB increased 2 times from 0.05 to 0.15 mm, Nusselt Number increased from 8794 to 163560, nearly 19 times. However, when VB increased 4 times from 0.05 to 0.25 mm, Nusselt Number increased to 683351, nearly 78 times. Therefore, a relatively large flank wear value could provide more space for heat convection which was in consistence with Fig.2 demonstrated. The wear duration would be increased sharply as flank wear value increased.

To further investigate the relationships between the flank wear value and heat transfer ability, a simplified calculation of dividing the heat flux and Nusselt Number by flank wear value was conducted and the results were shown in Fig.5a and 5b, respectively. As for heat flux per flank wear value (HpVB), as the flank wear value, also the cutting interface length increased, HpVB shown a decreased trend. As the flank wear value reached to the critical value, the heat accumulation would be enhanced significantly while the heat transfer ability tended to reach a limitation. And thus the tool would rapidly fail.

However, as for the heat convection effect, the increase of cutting interface length would provide more space for the existence of U-TBL, and thus resulting the heat convection effect per flank wear value increase accordingly. In this regard, large flank wear value shown advantages of both heat flux, i.e., absolute heat transfer ability and Nusselt Number, i.e., heat convection ability compared to the situations of small flank wear value. Therefore, during the tool wear progress illustrated in Fig.2, at the initial wear stage, the wear rates of HUVC and CC shown slight difference within a quite short during. As cutting continued, the wear rate of CC kept growing while that of HUVC slowed down and kept constant at a small value. The during of CC when flank wear from 0.21 to 0.25 mm was nearly 14 minutes while that of HUVC was 42 minutes, 3 times. When the tool wear went into severe wear stage from 0.25 to 0.3 mm flank wear value, the duration of HUVC was about 25 minutes while that of CC was only 6 minutes, nearly 4 times longer. From this aspect, it could be concluded that the advantages of HUVC compared to CC was mainly determined during the stable and severe wear stages of flank wear value from 0.15 to 0.3 mm. The CFD results shown a consistent trend with the tool life.

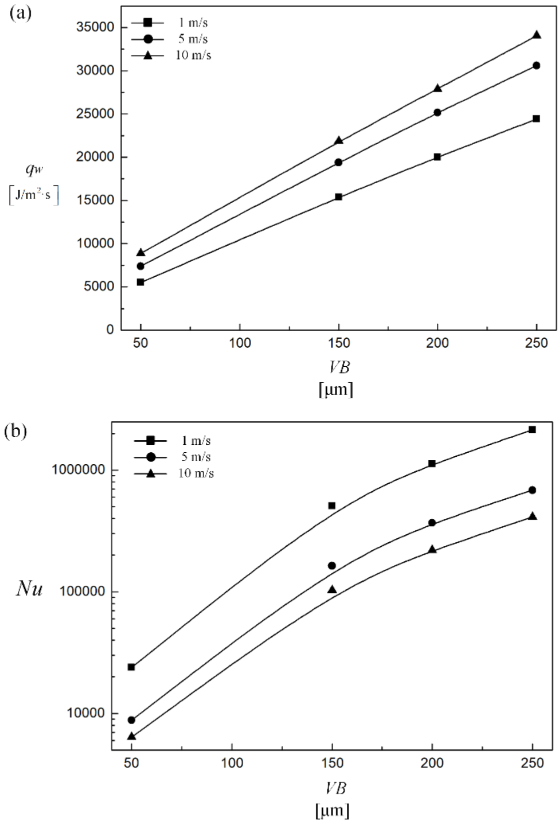

Fig. 4: (a) heat flux and (b) Nusselt Number within cutting interfaces of different flank wear VB at cutting speeds of 1, 5 and 10 m/s, respectively. Data of VB=0.2 mm was cited and modified from [Zhang 2023].

4.2 Transient states within cutting interfaces

Transient states within cutting interfaces were also demonstrated from Fig.6 to Fig.8 for the inlet velocity of 1, 5 and 10 m/s, respectively.

In Fig.6a, when the inlet coolant velocity was just 1 m/s, the existence of U-TBL lasted 40%, 45% and 45% of one vibration period for the flank wear value of 0.05, 0.15 and 0.25 mm, respectively. When the duty cycle was 0.5, the occupation percentage of U-TBL during the noncutting duration was 80%, 90% and 90%, respectively. In this regard, during the whole heat transfer duration, the well field synergy effect would occur which meant huge heat transfer ability enhancement. Seen in Fig.6b, when the flank wear value was only 0.05 mm, almost all the created space for heat transfer was well synergy effect zone even though the U-TBL nearly disappeared. When in Fig.6c, as the cutting interface length increased, the well synergy zone was appeared in the middle. Moreover in Fig.6d, it was still remained at the first half of the cutting interfaces. When the inlet coolant velocity was small, the effect of ultrasonic vibration was strong compared to the inlet coolant. In this regard, the reversed flow caused by negative pressure due to the fast space creating at the moment of tool just disengagement from workpiece. Even though during the interfaces opening process, the inlet coolant was too slow to fulfill the created space and the U-TBL was remained within the cutting interfaces almost during the whole noncutting duration. However, referred to the position of well synergy effect zone demonstrated in Fig.6b2, if the flank wear value turned to smaller, the U-TBL might be rapidly disappeared and the well synergy effect would be weakened. This could be used to explain the tool wear rate during the initial wear stage. Even though ultrasonic vibration was applied and the cutting interfaces were opened, the insufficient heat transfer space and low U-TBL occupation percentage due to the small flank wear value were the main transient states.

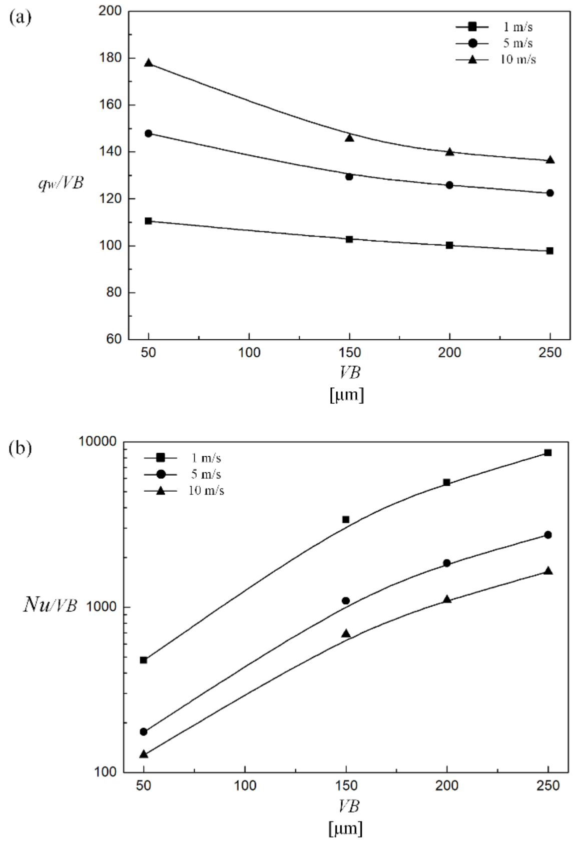

Fig. 5: (a) heat flux and (b) Nusselt Number per unit characteristic length within cutting interfaces of different flank wear VB at cutting speeds of 1, 5 and 10 m/s, respectively. Data of VB=0.2 mm was cited and modified from [Zhang 2023].

When the inlet coolant velocity was 5 m/s shown in Fig.7. The balance of the ultrasonic vibration effect and inlet coolant effect had a great change. Seen in Fig.7a, the existence of U-TBL during the noncutting duration wad only 40% when the flank wear value was 0.05 mm. In this regard, the main heat transfer ability enhancement effect, i.e., well field synergy effect only lasted 40% during the noncutting duration. The remained 60% duration was the result of inlet coolant velocity for thinning stable thermal boundary layer (S-TBL) according to [Zhang 2023] (Fig.7b). However, when the flank wear value reached to 0.15 and 0.25 mm, the existences of U-TBL respectively returned back to 70% (Fig.7c) and 80% (Fig.7d) which might hugely increase the heat transfer ability. This could be used to describe the huge heat convection enhancement discussed in Fig.4b. Therefore, the large flank wear value could provide enough space for the U-TBL to travel driving by the inlet coolant velocity. As it increased, the inlet coolant would rush into the created space and push the U-TBL to the outlet. When the flank wear value was only 0.05 mm, the U-TBL was rapidly pushed out from the cutting interfaces within a during of 10 μs. When the tool wear went into stable wear stage, it could last for nearly 20 μs which meant sufficient heat convection. In addition, the increased inlet coolant velocity amplitude could also enhance the heat transfer ability by itself $\vec{U}$ and the thinned thermal boundary layer which could decrease the synergy angle θ and increase the temperature gradient $gradT$ simultaneously according to Formula (1). The inlet coolant velocity amplitude took the leading role instead of ultrasonic vibration.

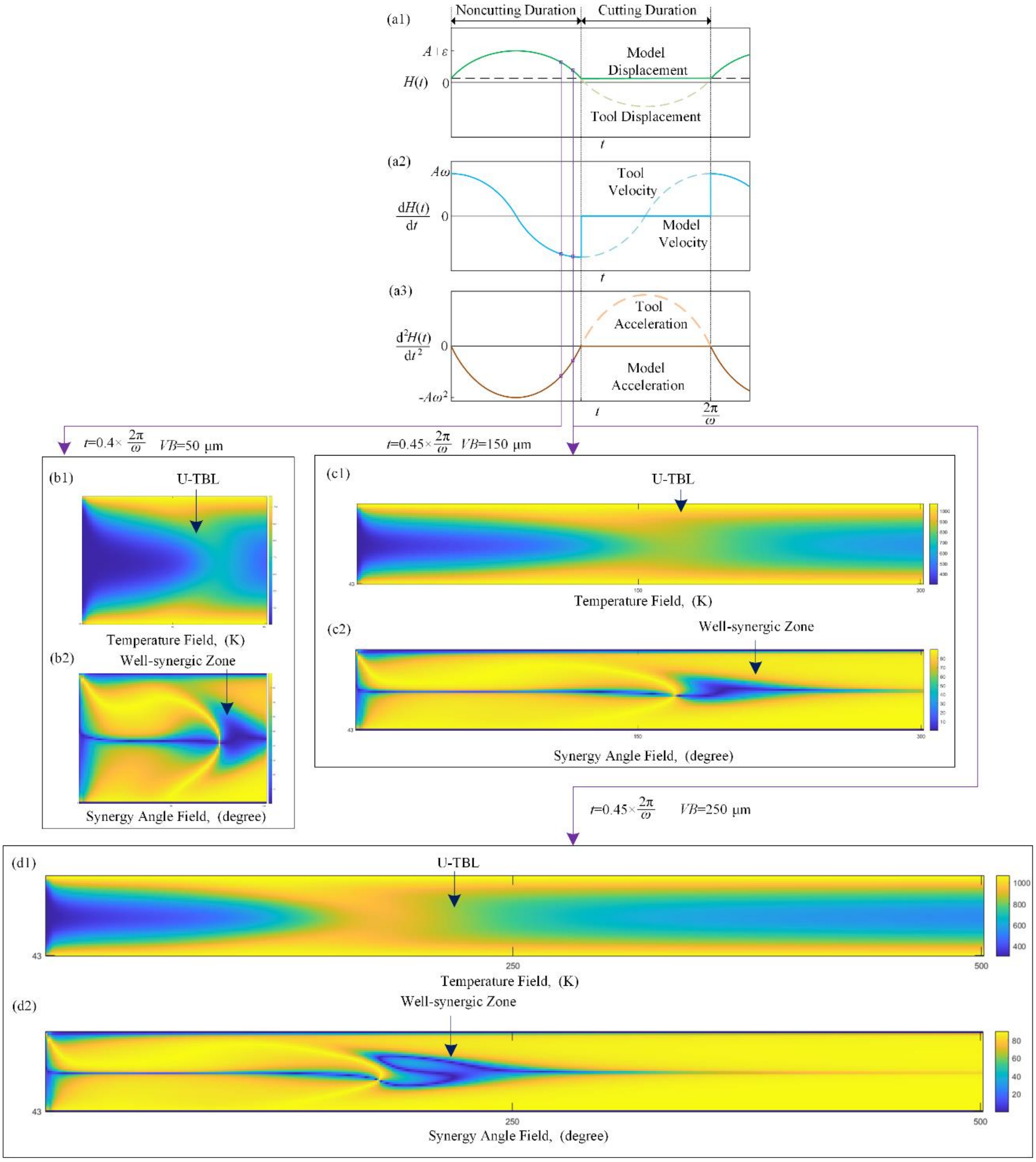

Fig. 6: CFD results of 1 m/s inlet velocity, (a) dynamic mesh boundary wall, 1, displacement, 2, vibration velocity, 3, vibration acceleration. selected moments of U-TBL disappearance of (b) VB=0.05 mm, (c) VB=0.15 mm and (d) VB=0.25 mm. 1 and 2 are temperature and synergy angle fields, respectively.

As the inlet coolant velocity increased to 10 m/s, the advantages of large flank wear value were much more obvious. In Fig.8a, when the flank wear value was only 0.05 mm, the existence of U-TBL sharply decreased to 20% of noncutting duration, which meant only 5 μs for well field synergy effect. The cooling mechanism of the remained 20 μs was determined by tradition heat convection. The effect of ultrasonic vibration was only obtained just at the beginning of the tool wear stage which could not lasted for a long time. When the flank wear value increased to 0.15 mm in the initial-stable transition stage, the existence of U-TBL increased to 50% of noncutting duration (Fig.8c). It was still smaller than 70% shown in Fig.7c. In this regard, the heat convection effect was weaker which kept consistent of the varying trend of Nusselt Number in Figs.4b and 5b. As the tool wear continued and reached to 0.25 mm in Fig.8d, it could be found that the existence of U-TBL was 70% of the noncutting duration. Similar discussions to Fig.7 could be also drawn. The percentage of U-TBL for different tool wear stages in Figs.6 to 8 were summarized in Table 1. It could be found that the duration variation was much more sensitive at a small flank wear value compared to the results of large flank wear values.

From the above analysis, it could be found that the heat transfer ability was evaluated from comprehensive aspects. Firstly, ultrasonic vibration was the foundation of the heat transfer. Different from CC, it provided opened cutting interfaces to let the coolant penetrate in and have direct contact with the heat source. This was the primary innovation of HUVC. Based on this foundation, the cooling mechanism has been totally changed and could be listed as a new mechanism for this machining approach. Then the heat transfer ability was the balanced effect of ultrasonic vibration and inlet coolant velocity. The former one could hugely increase the heat convection effect due to the existence of U-TBL while the later one could direct enhance the heat transfer ability by increasing the coolant velocity according to Formula (1). Therefore, during the tool wear process, this balance was also varied dynamically as the flank wear land grown.

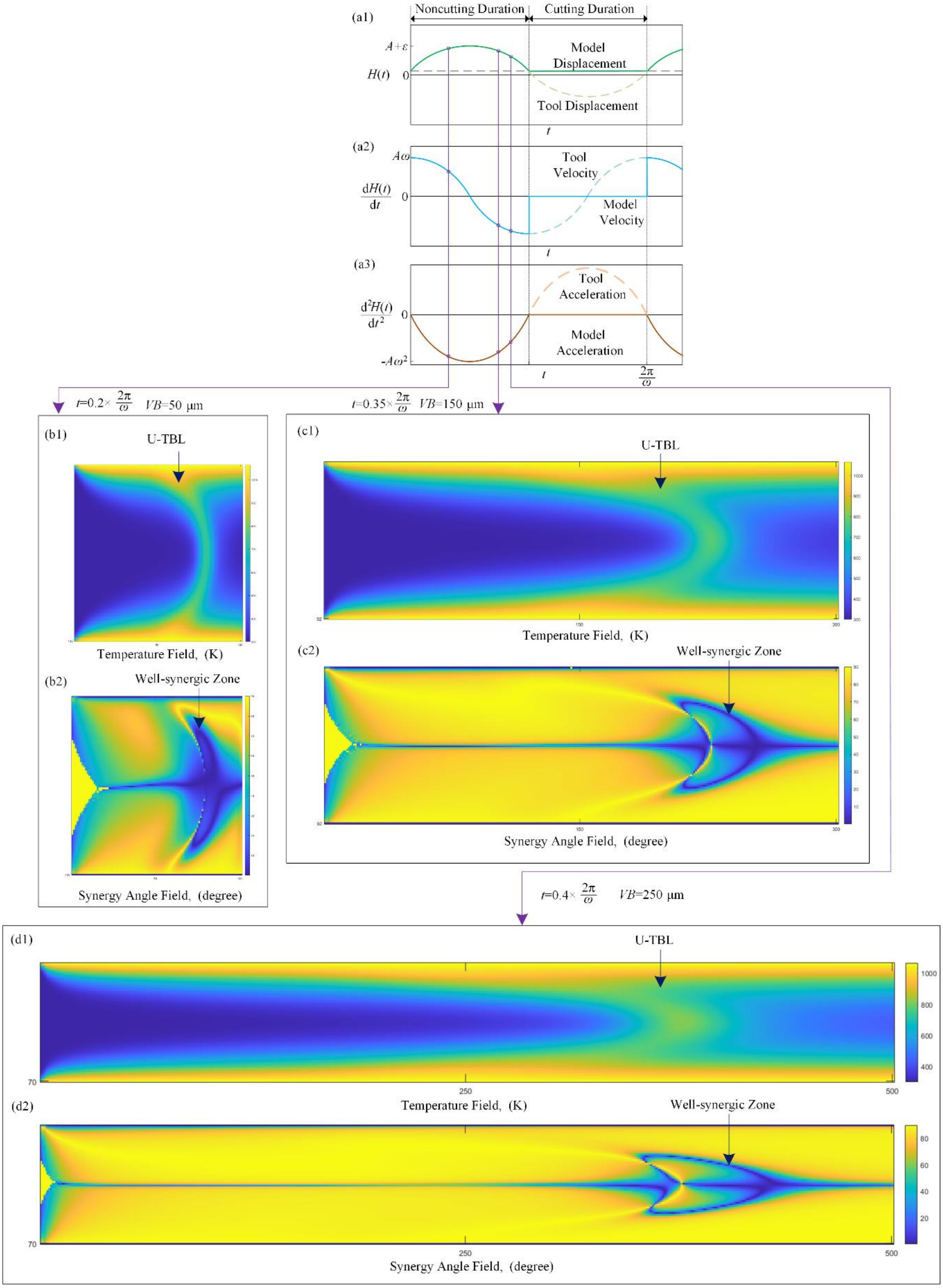

Fig. 7: CFD results of 5 m/s inlet velocity, (a) dynamic mesh boundary wall, 1, displacement, 2, vibration velocity, 3, vibration acceleration. selected moments of U-TBL disappearance of (b) VB=0.05 mm, (c) VB=0.15 mm and (d) VB=0.25 mm. 1 and 2 are temperature and synergy angle fields, respectively.

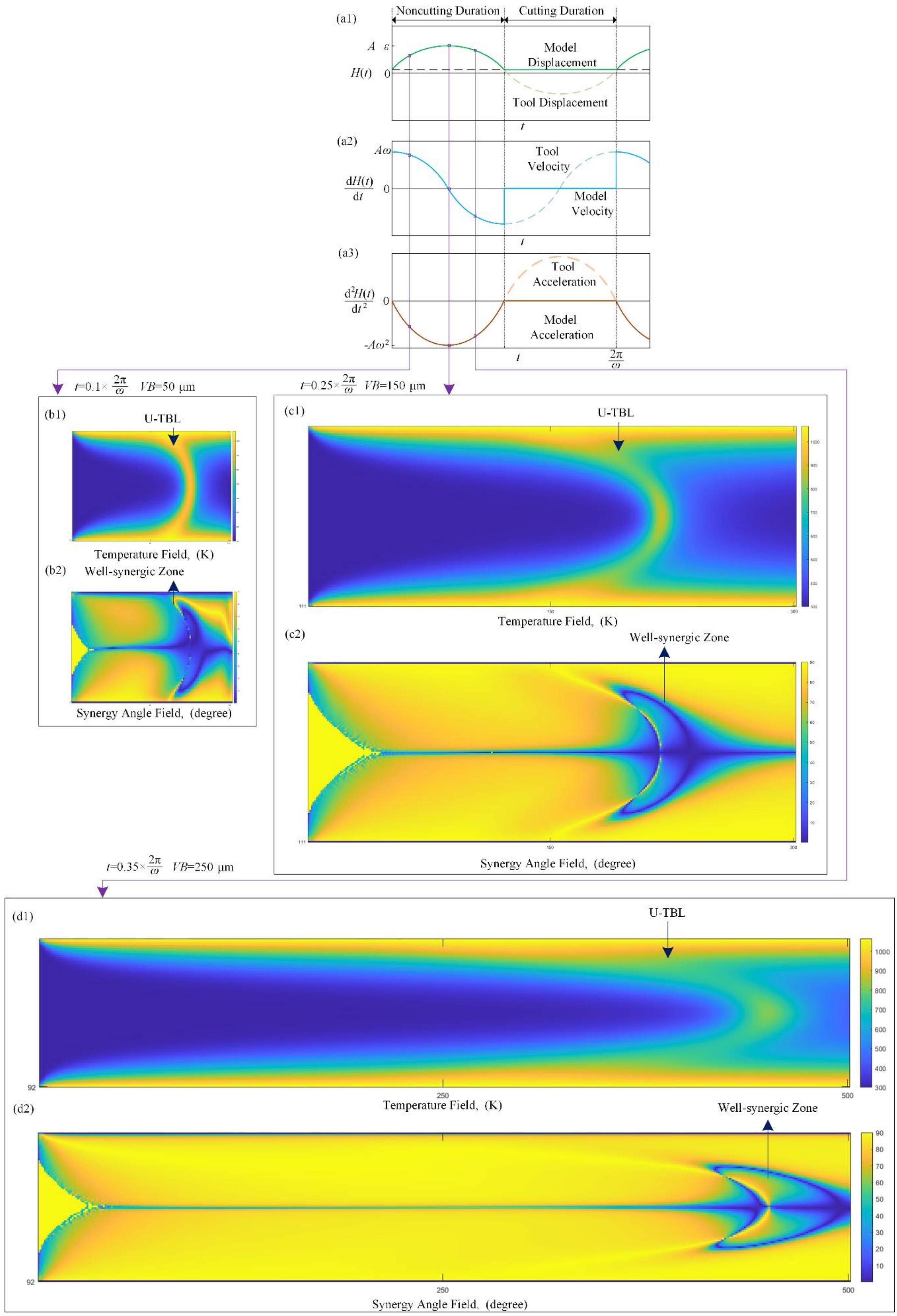

Fig. 8: CFD results of 10 m/s inlet velocity, (a) dynamic mesh boundary wall, 1, displacement, 2, vibration velocity, 3, vibration acceleration. selected moments of U-TBL disappearance of (b) VB=0.05 mm, (c) VB=0.15 mm and (d) VB=0.25 mm. 1 and 2 are temperature and synergy angle fields, respectively.

When the flank wear value was small at the initial stage, it could not provide enough space for the U-TBL to exist. In this regard, when the inlet coolant velocity increased to a certain value, the inlet coolant velocity took the leading role.

However, when the flank wear value got larger, it could provide more space for the U-TBL to exist. In this regard, the effect of ultrasonic vibration could take the leading role which could largely enhance the heat convection effect. Therefore, the tool wear rate was quite slow and smooth of HUVC compared to that of CC when the flank wear value was in a range of 0.15 to 0.3 mm. The benefits of HUVC were obtained mainly in this wear stage.

Tab. 1: Percentage of the existence of U-TBL in the noncutting duration.

Inlet coolant velocity	VB=0.05 mm	VB=0.15 mm	VB=0.25 mm
1 m/s	80%	90%	90%
5 m/s	40%	70%	80%
10 m/s	20%	50%	70%

5 SUMMARY

HUVC could provide opened cutting interfaces for heat transfer directly between the heat source and coolant. CFD results shown that during the stable tool wear stage, the heat transfer ability and heat convection effect could both be enhanced due to the suffienent heat transfer space provieded by the combined results of tool wear land profile and ultrasnoic vibration. The prolongation of existence duration of U-TBL was the key of heat flux increase which could be increased from 20 to 90 percent once apprppraite parameters were set. The results shared consistent varying trend with the tool life curves and it revealed that the advantages of HUVC were mainly obtained during the tool stable wear stages (VB=0.15-0.25 mm). This result could be used as a reference for further tool life prolongation of HUVC. The key was hidden behind the relationships between the tool wear progress and cutting temperaure control within the opened cutting interfaces.

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