清華大学深圳国际研究生院
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Thermomechanical simulation of Nickel-based Super Alloy(Inconel 718) using Abaqus

Final report

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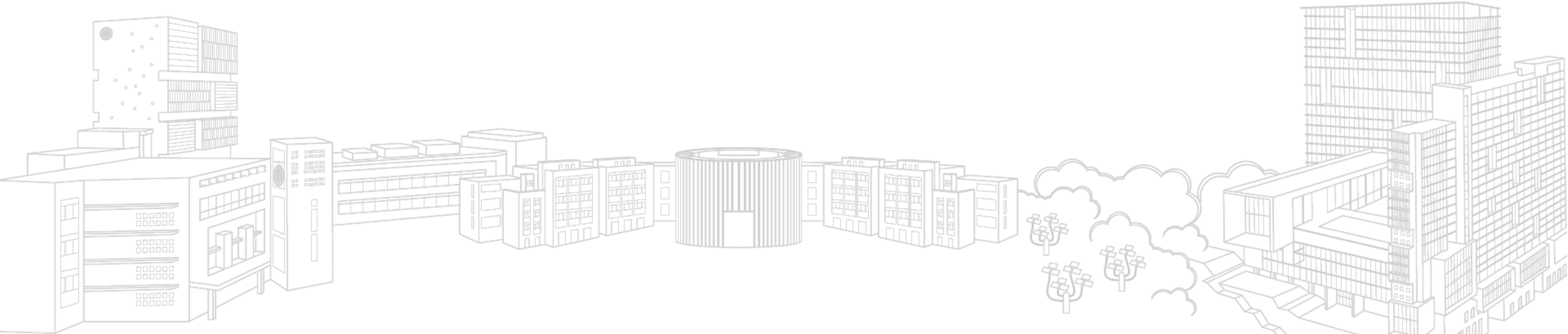
January 3, 2023



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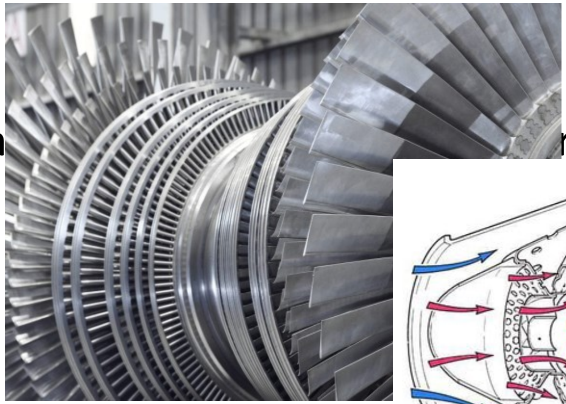
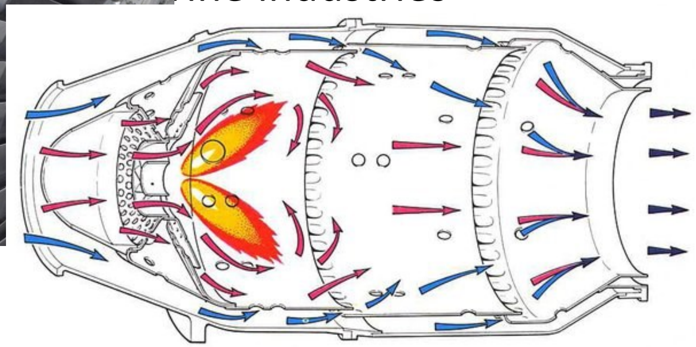
Part one

Background and Physics

Background

Inconel 718 nickel-based alloy (GH4169 in GB) -- Widely used in rine industries





Advantages[1]:

High Stiffness and ***Strength*** at high temperature(850 °C)

High Dynamic Shear Strength

Extremely ***low Reactivity*** in highly corrosive environment

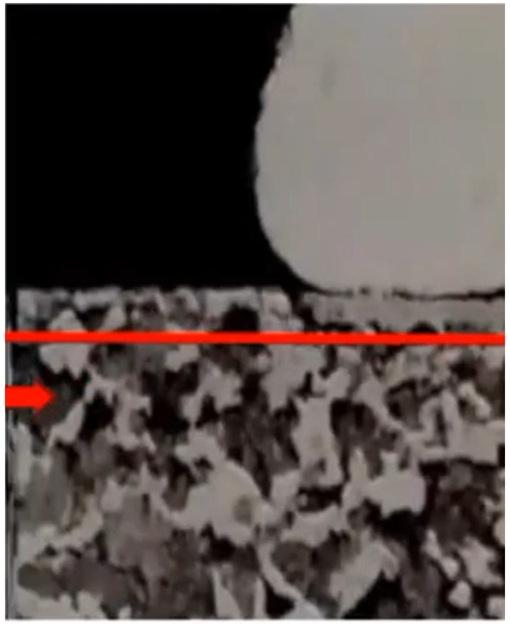
Examples: Turbine Blades and Combustion Chamber in turbine engine

Poor machinability[1]:

Adhere with tool——built up edge(积屑瘤)

Strain hardening——harder for next cut

Low thermal conductivity——high temperature in cutting zone



Simulation

Proper *Cutting Parameters* and *Tools*

[1] Rinaldi S, Imbrogno S, Rotella G, et al. Physics based modeling of machining Inconel 718 to predict surface integrity modification[J]. Procedia CIRP, 2019, 82: 350-355.

Physics

1. Workpiece
2. Tool
3. Contact

thermal and mechanical model

Thermomechanical coupling modeling[2]:

1.1 Workpiece thermal model: **The first law of thermodynamics**

$$\rho \boxed{c_p} \frac{\partial T}{\partial t} - \frac{\partial}{\partial x_i} \cdot \left(\boxed{\lambda} \frac{\partial T}{\partial x_i} \right) = \dot{q}_p$$

Specific heat capacity c_p

Thermal conductivity λ

Thermal expansion α

Temperature dependent

1.2 Workpiece mechanical model:

Elastic model: **Hooke's law**

$$\sigma_{ij} = \boxed{\mathcal{C}_{ijkl}} \left(\varepsilon_{kl}^{e} - \alpha \Delta T \delta_{kl} \right)$$

$$\mathcal{C}_{ijkl} = \frac{\boxed{E}}{(1+\boxed{\nu})(1-2\nu)} \delta_{ij}\delta_{kl} + \frac{E}{(1+\nu)} \delta_{ik}\delta_{jl}$$

Young's modulus E

Possion's ratio ν

Temperature dependent

[2] Bedzra R. Finite element simulation of two dimensional orthogonal cutting process and comparison with experiments[D]. GER: RWTH Aachen University, 2013.

Physics

1. Workpiece
2. Tool
3. Contact

thermal and mechanical model

Thermomechanical coupling modeling[2]:

1.2 Workpiece mechanical model:

Plastic model: **Johnson-Cook plasticity model**

$$\underbrace{\sqrt{\frac{3}{2}}\,\|\sigma_{ij}^{D}\|}_{\sigma_{\mathrm{vM}}} = \left(\boxed{\mathrm{A}} + \boxed{\mathrm{B}}\left(\underbrace{\int \|\dot{\varepsilon}_{ij}^{p}\|\,\mathrm{dt}}_{\varepsilon}\right)^{\boxed{\mathrm{n}}}\right)\left(1 + \boxed{\mathrm{C}}\ln\left(\frac{\overbrace{\|\dot{\varepsilon}_{ij}^{p}\|}^{\dot{\varepsilon}}}{\boxed{\dot{\varepsilon}_0}}\right)\right)\left(1 - \left(\frac{\mathrm{T} - \boxed{\mathrm{T}_0}}{\boxed{\mathrm{T}_\mathrm{m}} - \mathrm{T}_0}\right)^{\boxed{\mathrm{m}}}\right)$$

Coefficients A, B, C, m, n

Reference strain rate $\dot{\varepsilon}_0$

Reference temperature T_0

Melting temperature T_m

Material separation (chip formation) model: **Johnson-Cook damage model**

$$\varepsilon_f = \left(\boxed{\mathrm{d}_1} + \boxed{\mathrm{d}_2}\exp\left(-\boxed{\mathrm{d}_3}\frac{\sigma_\mathrm{m}}{\sigma_{\mathrm{vM}}}\right)\right)\left(1 + \boxed{\mathrm{d}_4}\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)\left(1 + \boxed{\mathrm{d}_5}\left(\frac{\mathrm{T} - \mathrm{T}_0}{\mathrm{T}_\mathrm{m} - \mathrm{T}_0}\right)\right)$$

Stress triaxiality on fracture　Strain rate　Temperature

Material dependent parameters

d_1, d_2, d_3, d_4, d_5

Reference temperature T_0

Melting temperature T_m

Reference strain rate $\dot{\varepsilon}_0$

[2] Bedzra R. Finite element simulation of two dimensional orthogonal cutting process and comparison with experiments[D]. GER: RWTH Aachen University, 2013.

Physics

1. Workpiece
2. Tool
3. Contact

thermal and mechanical model

Thermomechanical coupling modeling[2]**:**

2 Tool mechanical and thermal model:

Elastic model: **Hooke's law**

Thermal model: **The first law of thermodynamics**

3.1 Contact mechanical model: **Coulomb's friction law**

$$\tau_f = \boxed{\mu}\sigma_n$$

Friction coefficient μ

3.2 Contact thermal model:

Contact between tool and chip is thermally perfect

Boundaries are assumed to be at room temperature(20℃)

Heat loss due to convection and radiation to surroundings is not taken into account

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Part two

Properties

Worpiece properties

1.1 Workpiece dimension

Length	Height	Cutting zone height
5	2	0.1

1.2 Workpiece thermal properties

T (°C)	0	100	200	300	400	500	600	700	800	900	1000	1100	120
c_p(J/(kg • °C))	440	470	480	490	500	520	550	600	660	650	660	700	71

T (°C)	0	100	200	300	400	500	600	700	800	900	1000	1100	120
λ(N/(s • °C))	10	11	13	15	18	19	21	25	26	25	25	29	31

T (°C)	0	50	100	150	200	250	300	350	400	450	500	550	600	650
α(10^{-6}/°C)	13	13.05	13.1	13.3	13.5	13.7	13.8	13.9	14.1	14.25	14.3	14.6	15	15.3

Workpiece properties

1.3 Workpiece mechanical properties

Elastic:

T (°C)	E (GPa)	v
20	217	0.3
871	155.9	0.3

Plastic:

$\dot{\varepsilon}_0$ (1/s)	T_0 (°C)	T_m (°C)	A(MPa)	B(MPa)	C(MPa)	n	m
10^{-3}	20	1297	1485	904	0.015	0.777	1.689

Material seperation:

d_2	d_4
2.031	0.014

$$\varepsilon_f = \left(\boxed{d_1} + \boxed{d_2} \exp\left(\boxed{-d_3} \frac{\sigma_m}{\sigma_{vM}}\right)\right)\left(1 + \boxed{d_4} \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)\left(1 + \boxed{d_5}\left(\frac{T - T_0}{T_m - T_0}\right)\right)$$

Stress triaxiality on fracture   Strain rate   Temperature

Tool and contact properties

2.1 Tool dimension:

Rake angle(°)	Flank angle(°)	Radius(μm)
0	10	10

2.2 Tool thermal properties:

T (℃)	0	100	200	300	400	500	600	700	800	900	1000	1100	12
c_p(J/(kg • ℃))	200	210	220	240	245	250	255	260	260	260	260	260	2(

T (℃)	0	100	200	300	400	500	600	700	800	900	1000	1100	120
λ(N/(s • ℃))	100	94	90	82	76	69	66	65	65	65	65	65	65

$\alpha(10^{-6}/°C) = 540$

3.1 Contact friction coefficient:

$\mu = 0.5$

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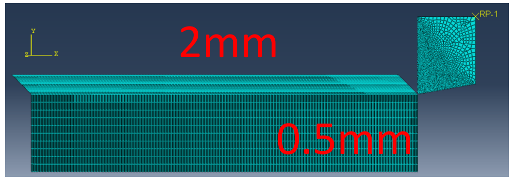
Part three

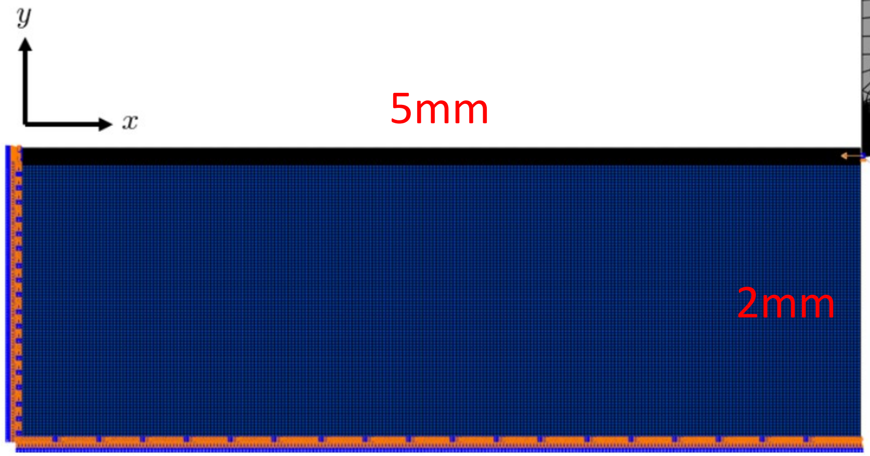
Result

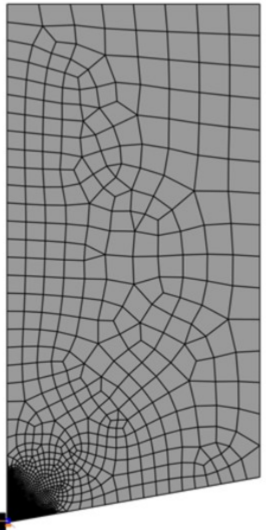
Simulation Result

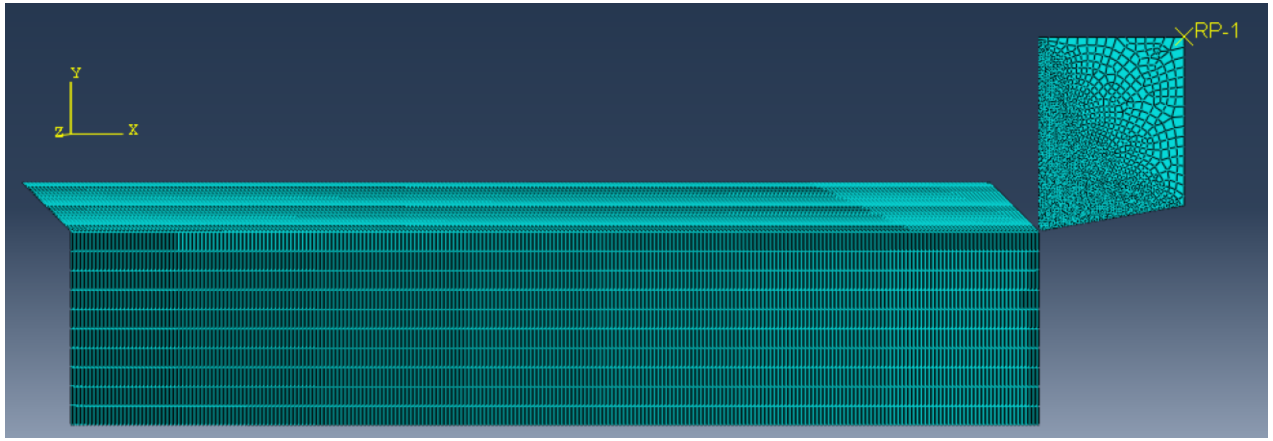
Different cutting speed: 20m/min, 40m/min, 80m/min

1. Cutting force and feed force
2. Temperature
3. Chip thickness







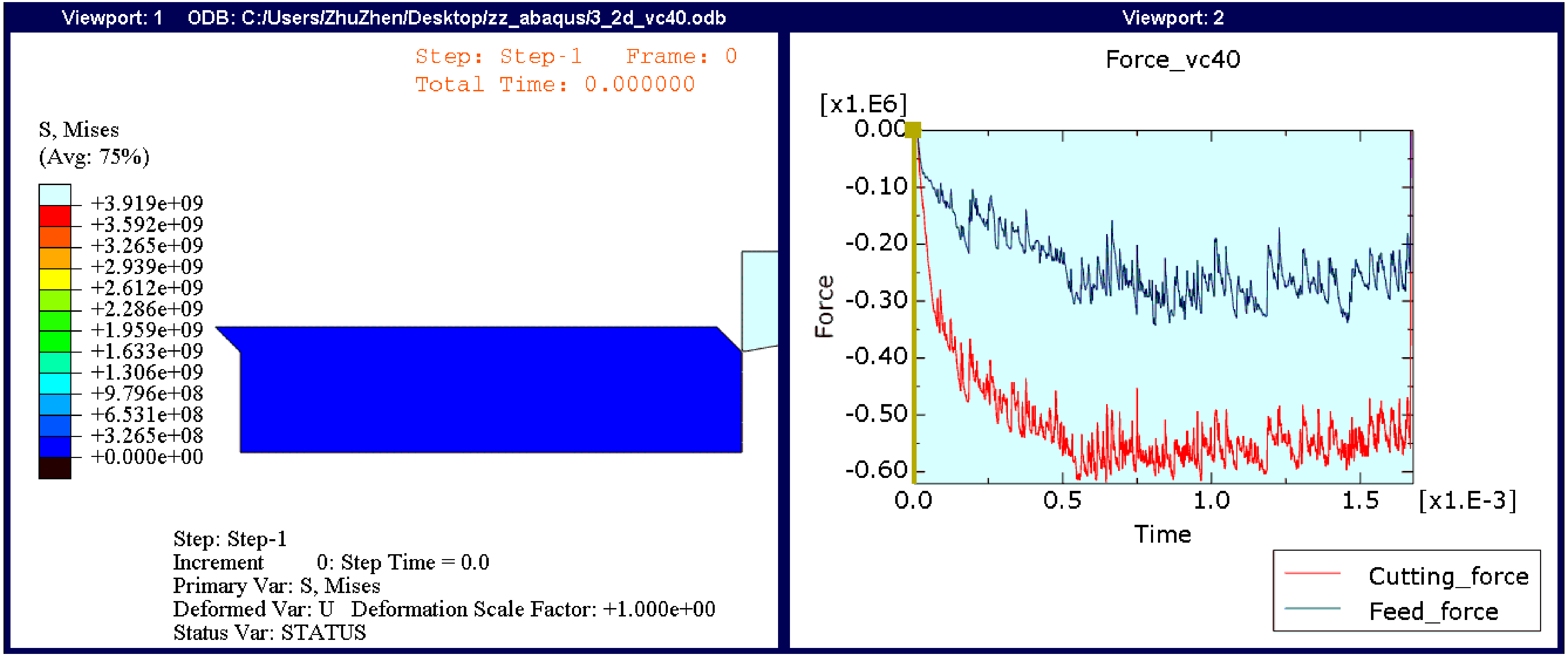


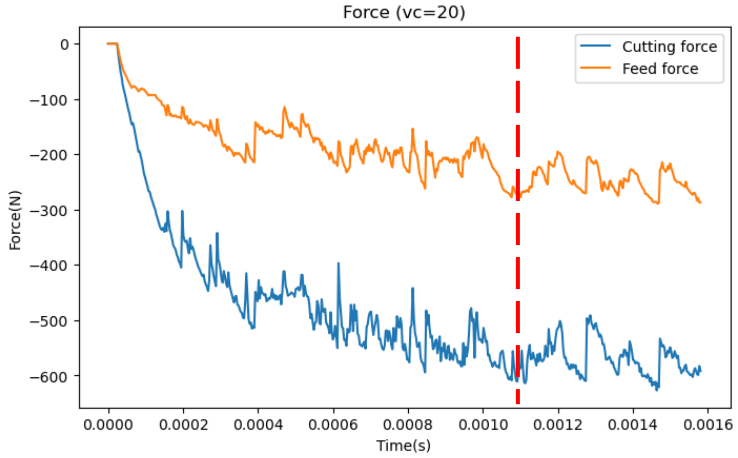
Force

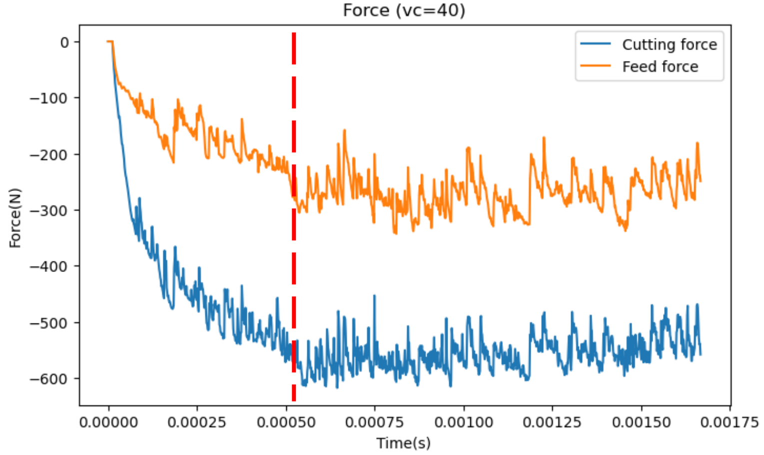
Cutting condition: 40m/min

Cutting force

Feed force







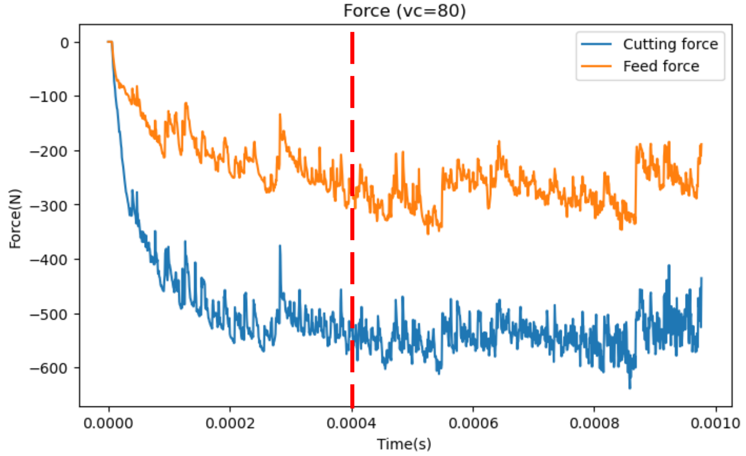


Table 1. My simulation result of average cutting force and feed force

	Vc=20m/min	Vc=40m/min	Vc=80m/min
Average cutting force(N)	569.53	557.52	537.16
Average feed force(N)	$\boxed{247.29}$	270.24	264.24

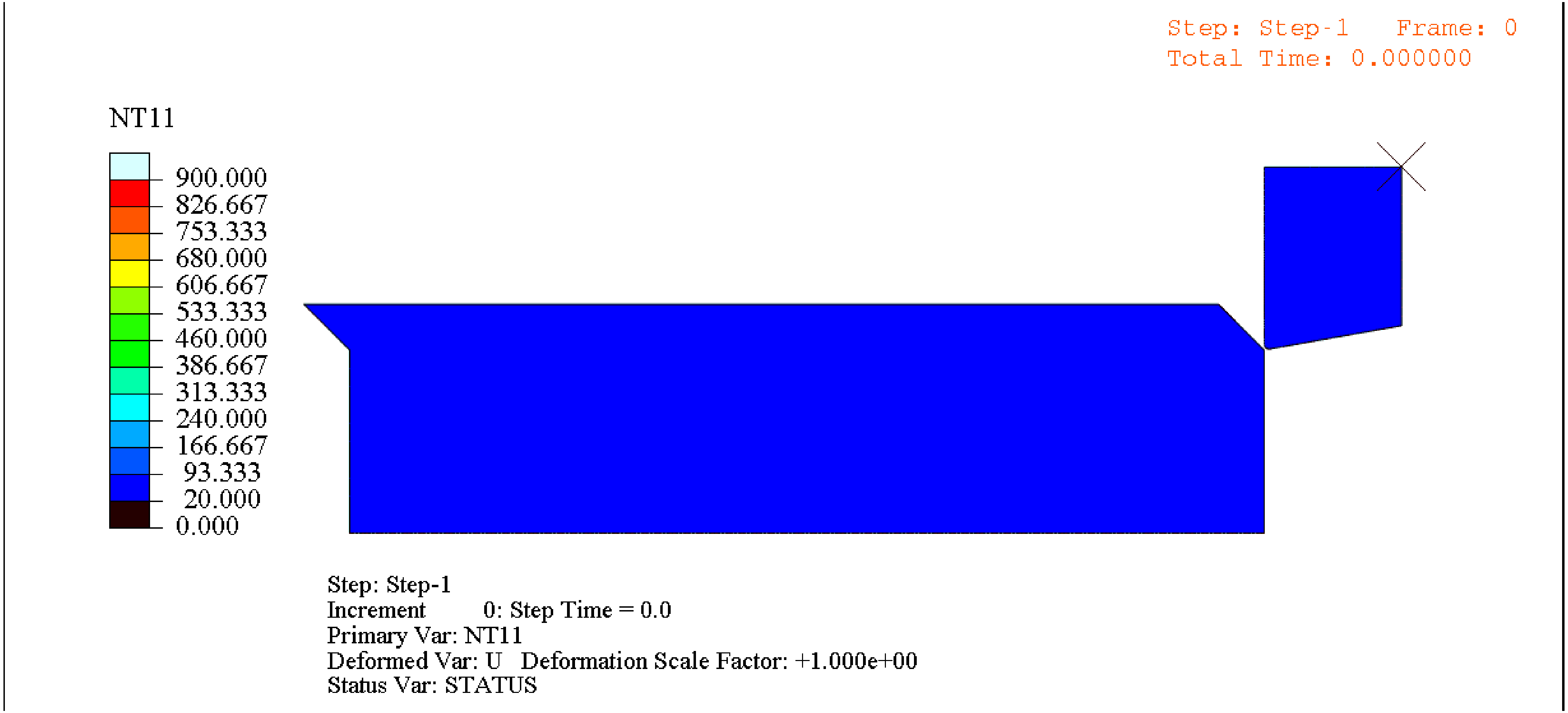
Table 2. Reference experiment and simulation result of average cutting force and feed force

	Vc=20m/min		Vc=40m/min		Vc=80m/min	
	Exp	Sim	Exp	Sim	Exp	Sim
Average cutting force(N)	269	285.42	234	259.83	232	254.90
Average feed force(N)	235	128.09	192	113.06	181	104.74

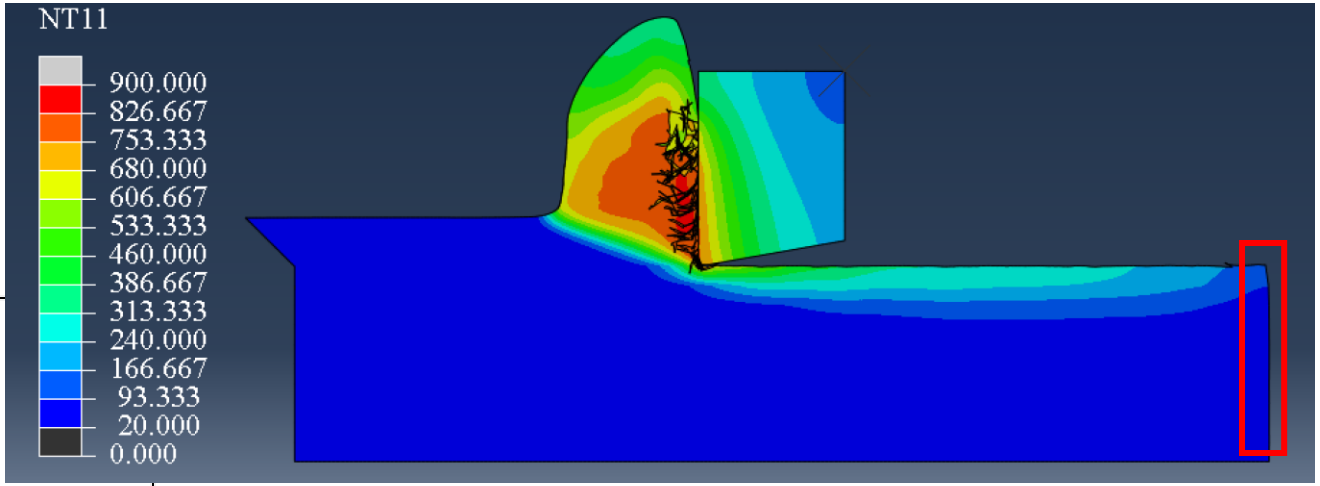
Discrepency:

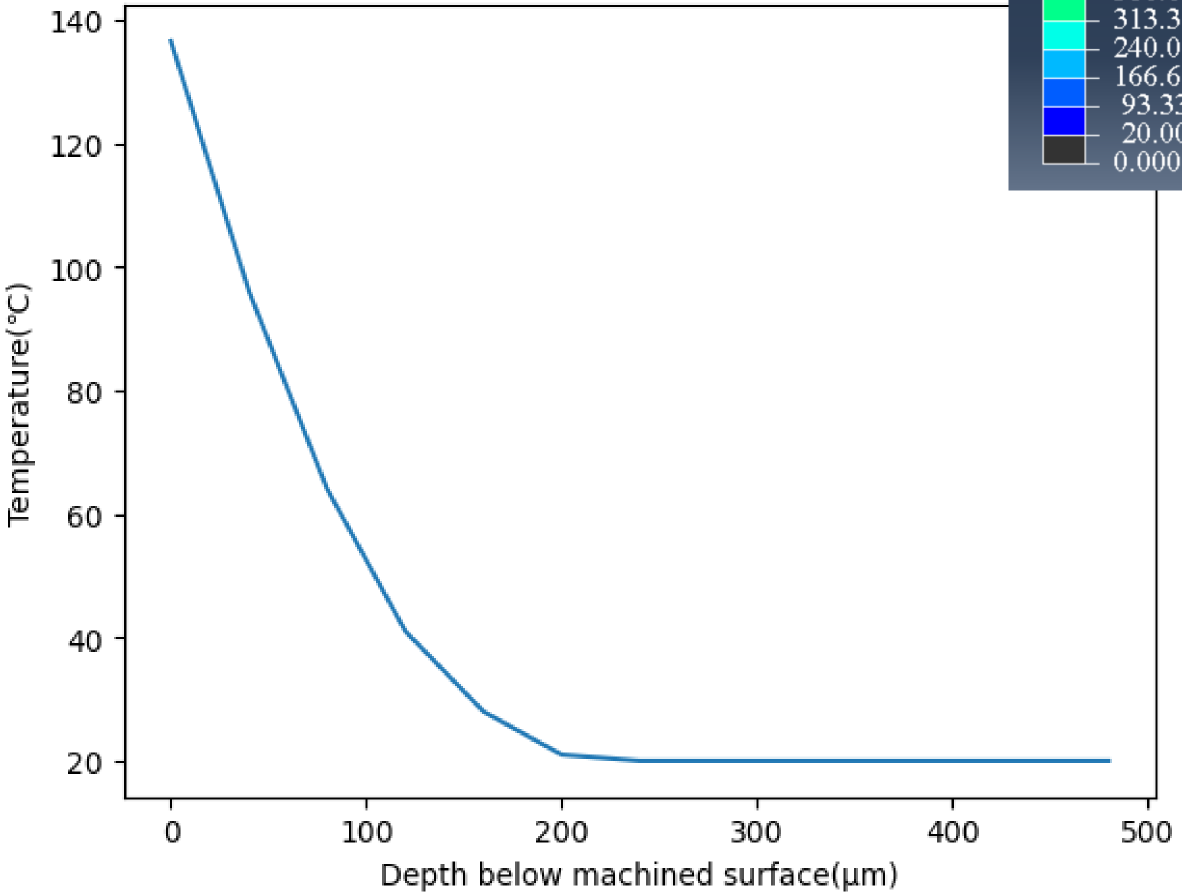
1. Two times difference
2. Insufficient data
3. Force scale (10^3)

Temperature

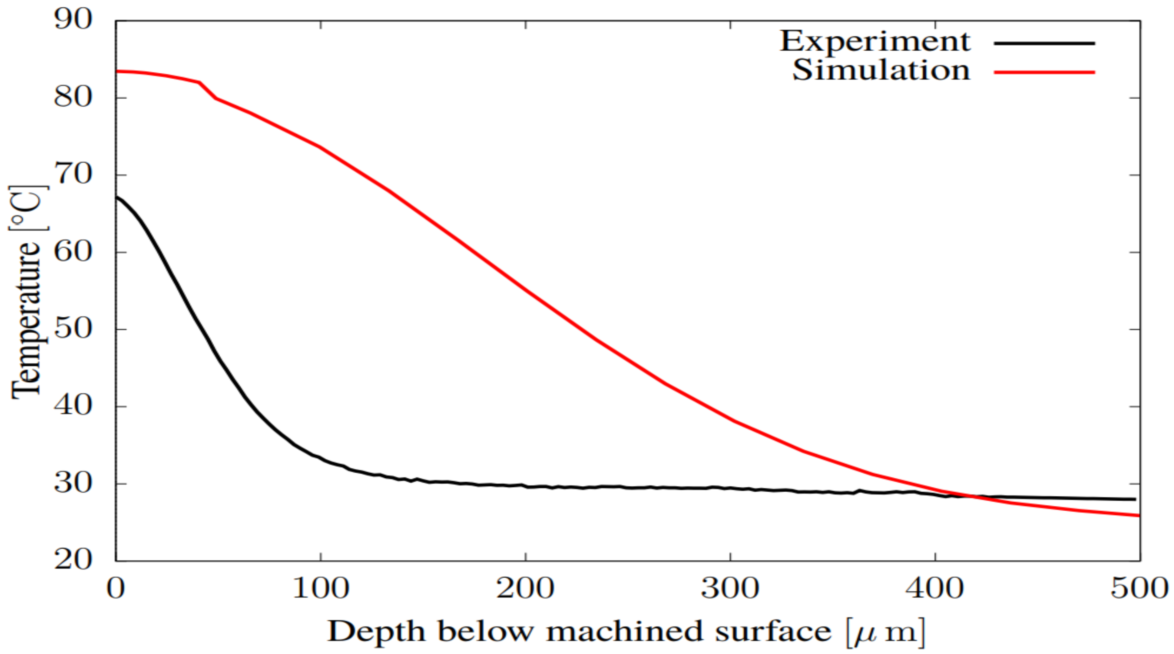


Temperature





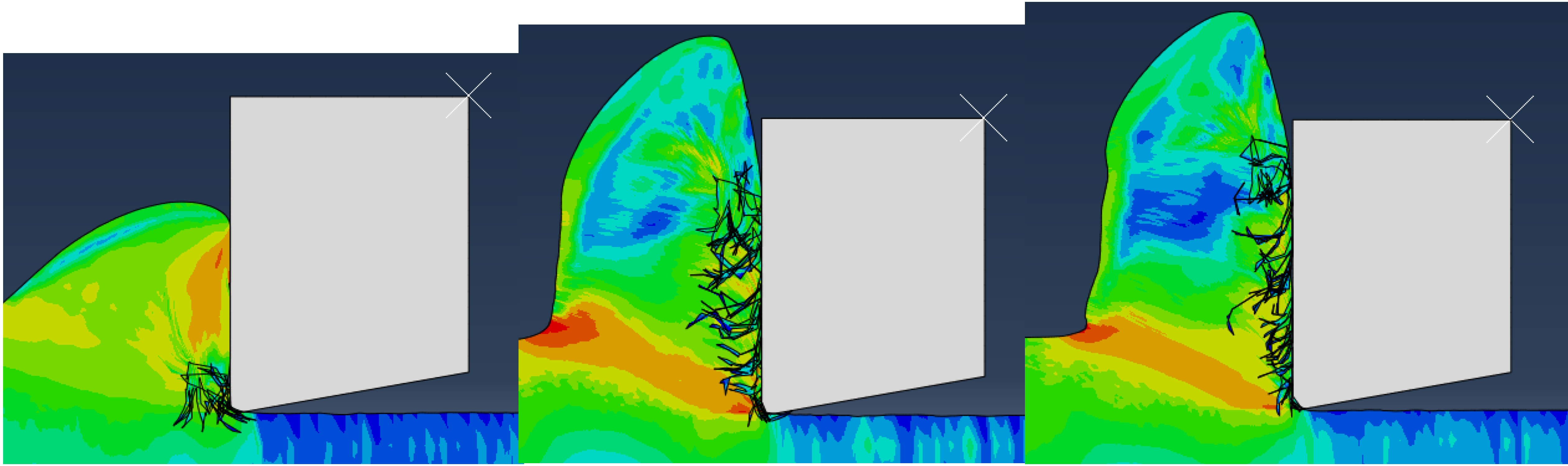
A distance of 1 mm behind the tool edge



A distance of 3.5 mm behind the tool edge

Chip morphology

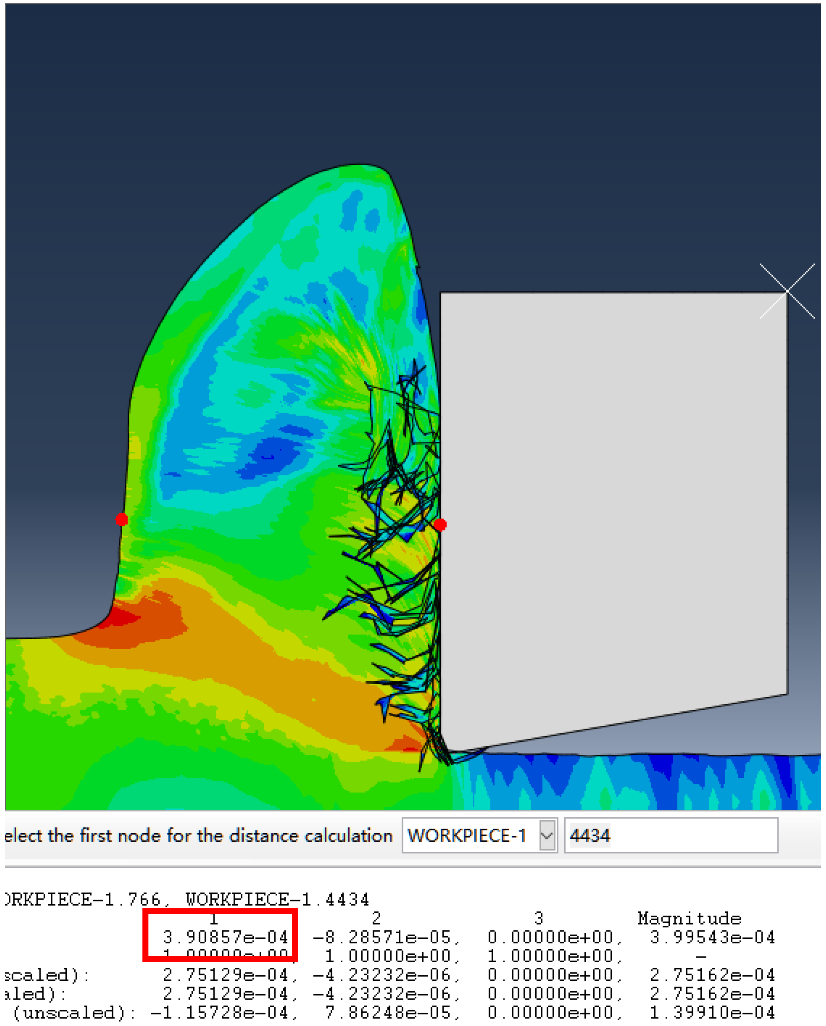
Vc=20m/min　　Vc=40m/min　　Vc=80m/min



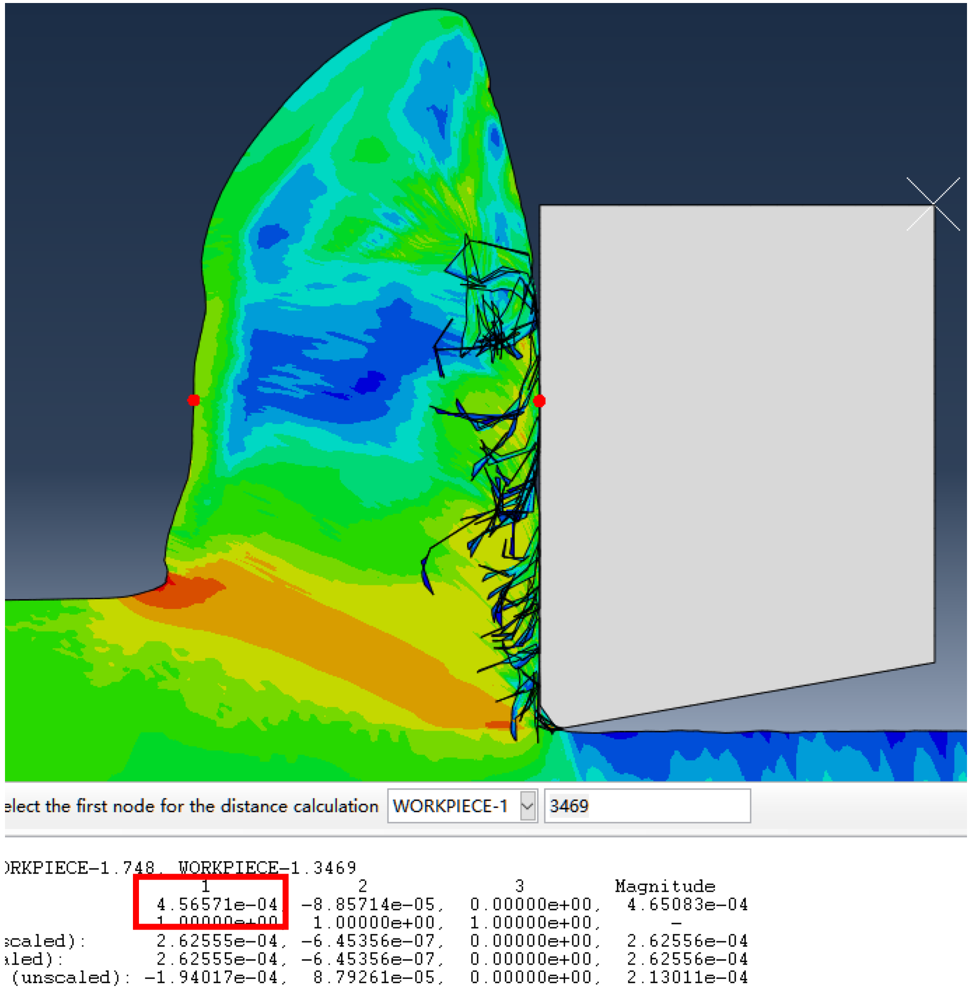
Conclusion: Continuous chip

Chip thinkness

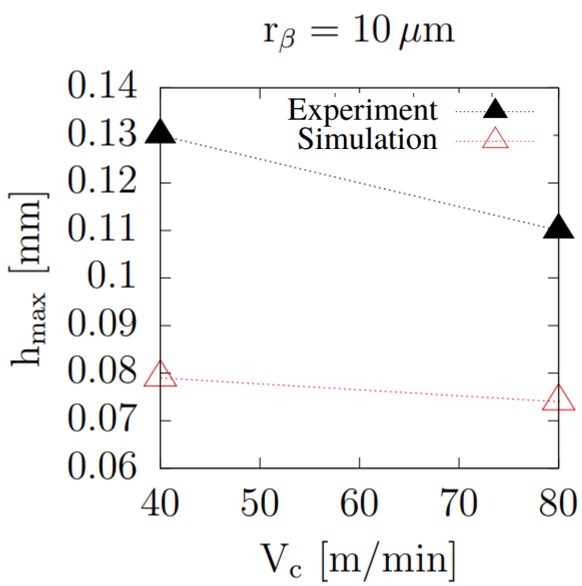
Vc=40m/min 0.39mm



Vc=80m/min 0.46mm



Reference



0.08mm

Discrepancy:

1. Different model

Thanks