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3D Simulation and Process Optimization of Laser Assisted Milling of Ti6Al4V

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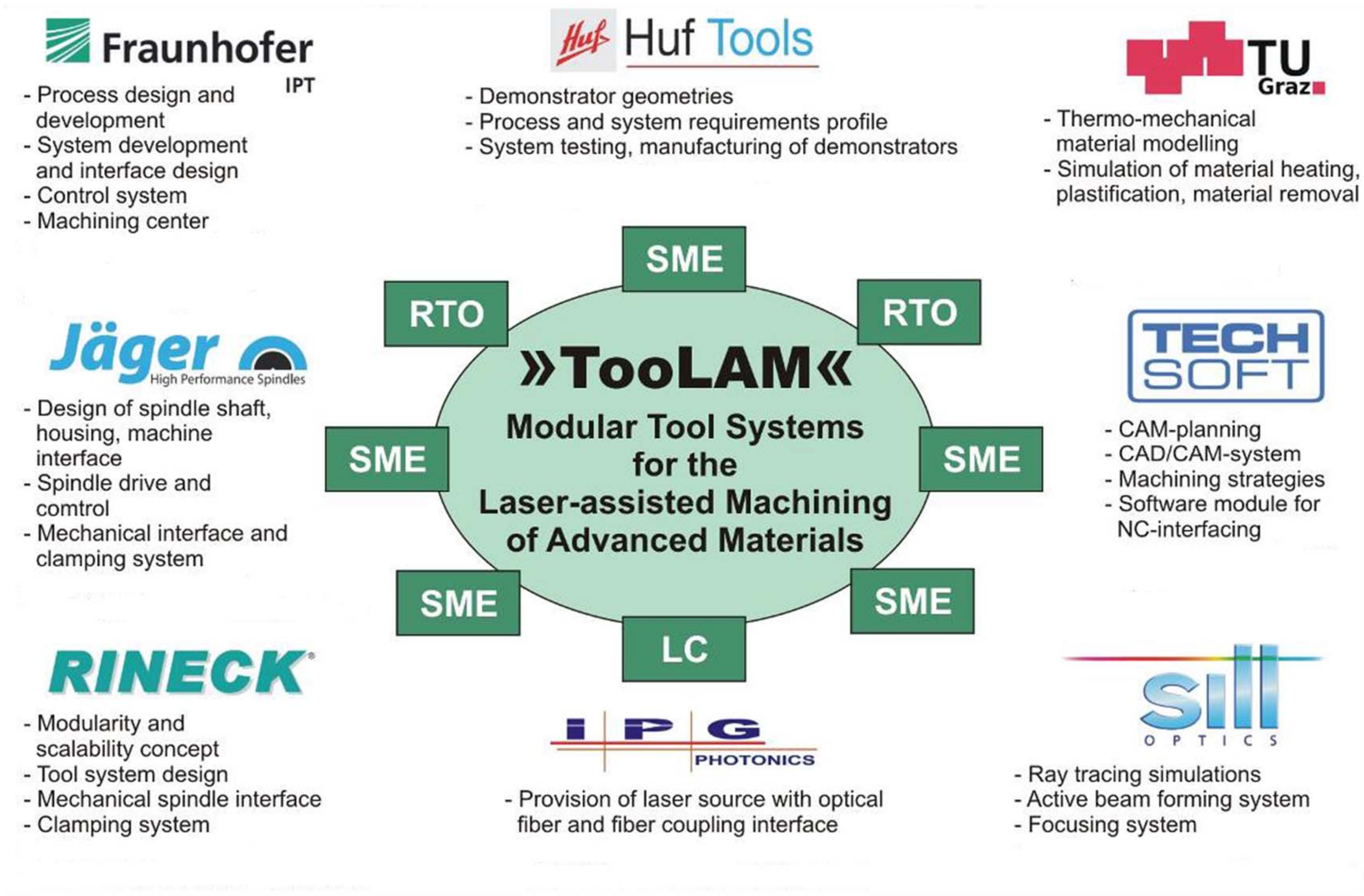
Overview

- Laser Assisted Milling
- Experimental Procedure
- Resulting Force Reduction
- 3D FEM of Laser Assisted Machining
- Model Validation
- Summary

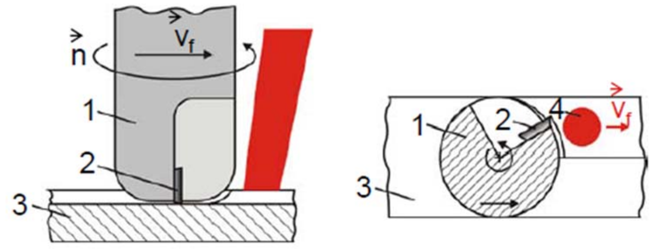
Technology Supplier



Laser Assisted Milling

Objective	Reduction of tool wear and increasing material removal rate
Approach	Reduction of process forces
Implementation	Reduction of material strength using laser heating of chip volume

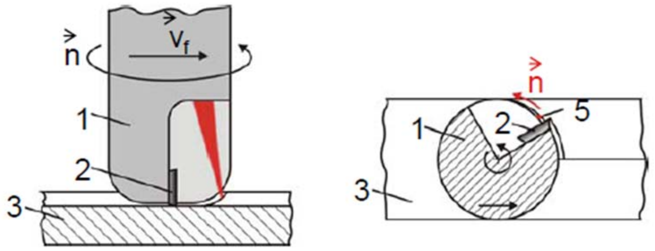
Previous Approach



- Irradiation in front of tool
- Movement of laser spot in feed direction
- Laser spot diameter ≈ width of cutting

➡ Extensive irradiation and thermal damage of workpiece

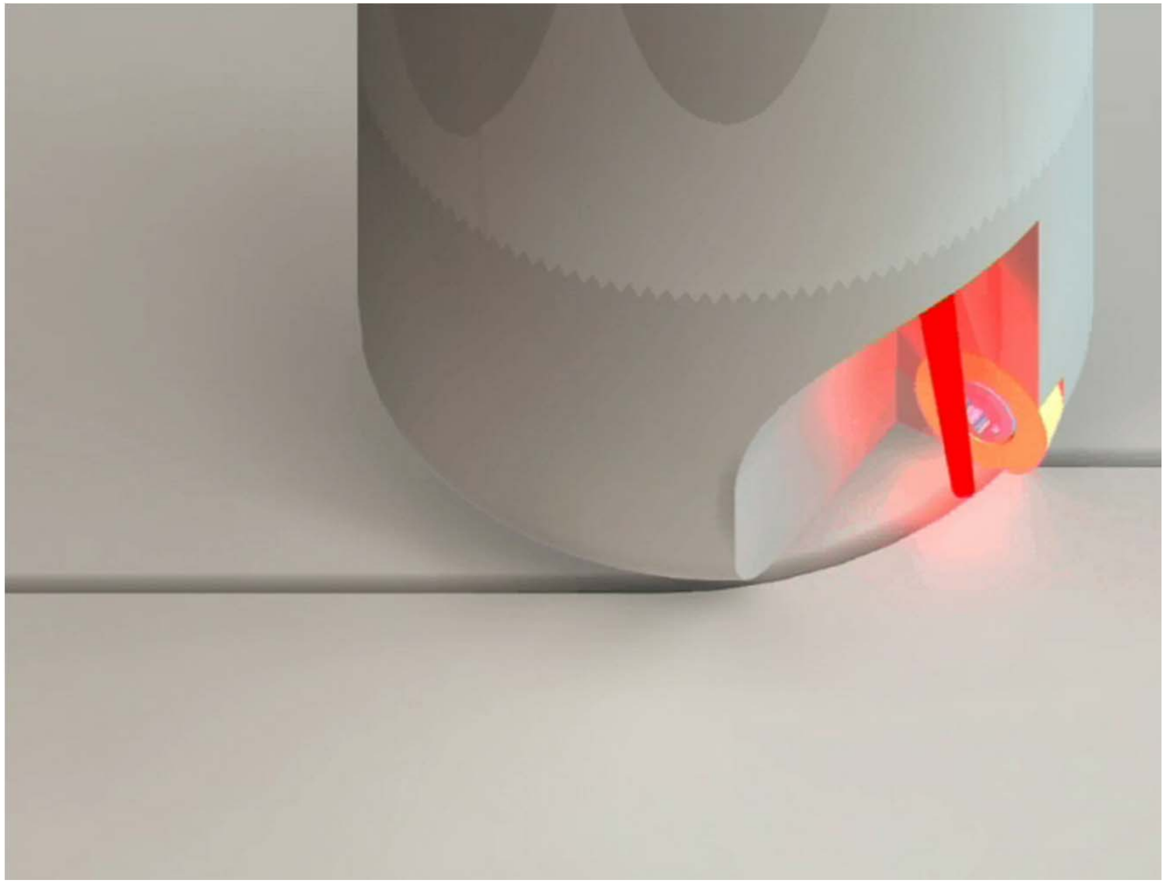
Novel Approach



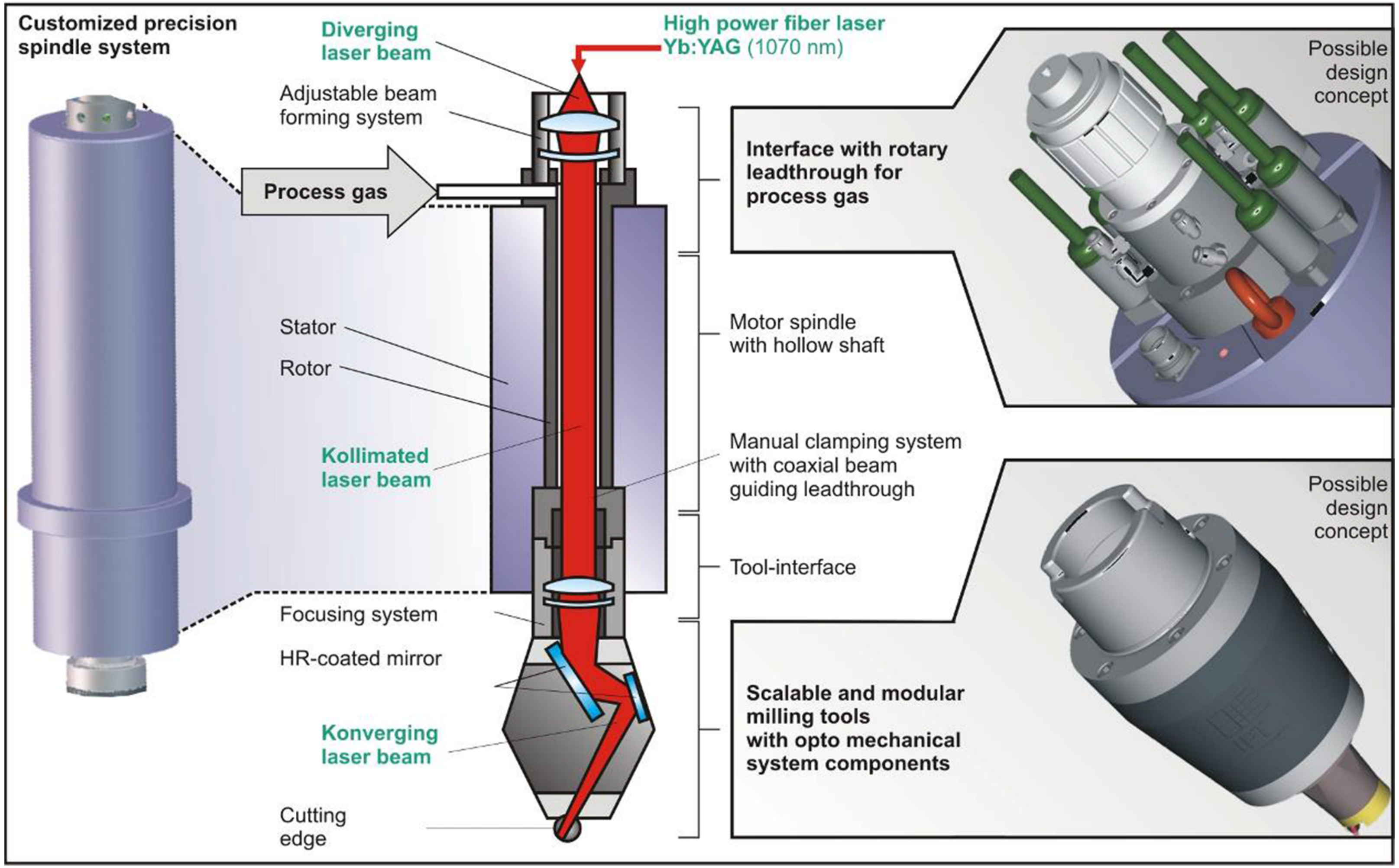
- Irradiation in front of tool tip
- Movement of laser spot with the cutter
- Laser spot diameter ≈ feed per tooth

➡ Exact irradiation and low thermal damage of workpiece

Working principle of the Novel Laser Assisted Milling



Tool principle of the Novel Laser Assisted Milling



Process Control Parameters

Laser Power is proportional to chip volume:

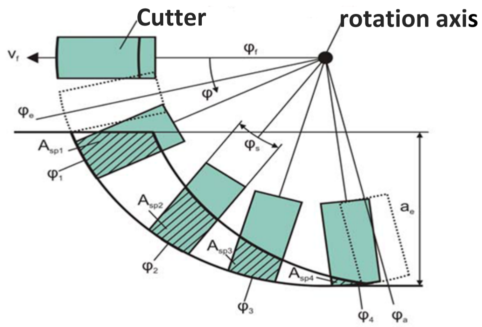
$$P_L(t) \sim V_{SP}(t)$$

$$V_{SP} = A_{SP} a_P \qquad A_{SP} = r_F \int_{\varphi_e}^{\varphi_a} h_{SP}(\varphi)\, d\varphi$$

Chip thickness :

$$\mathrm{h_{SP,Martellotti}}(\varphi) = \mathrm{r_F} + \mathrm{f_Z} \sin\varphi - \sqrt{r_F^2 - (\mathrm{f_z}\cos\varphi)^2}$$

- Provision of data
  - Cutter entrance angle (φ_e)
  - Cutter exit angle (φ_a)
  - Entrance chip surface ($A_{SP,e}$)
  - Exit chip surface($A_{SP,e}$)
- Programming of 4 data in NC-Code as linearly interpolated value
- Generation of high frequency analog laser signal




```
G00  X150.000 Y30.000 Z10.000
G00  X150.000 Y30.000 Z-1.000
F100 S00 M03
( Laser Ein )
G01 X105.000 Y30.000  WE250.000 WA250.000  AE0.000 AA0.000
G01 X100.000 Y30.000  WE270.000 WA250.000  AE2.000 AA1.000
G01 X5.000      Y30.000  WE270.000 WA250.000 AE2.000 AA1.000
G01 X0.000      Y30.000  WE250.000 WA250.000 AE0.000 AA0.000
( Laser Aus )
G01 X-50.000 Y30.000 Z-1.000
G00 X-50.000 Y30.000 Z10.000
```

Laser Heat Source Modeling

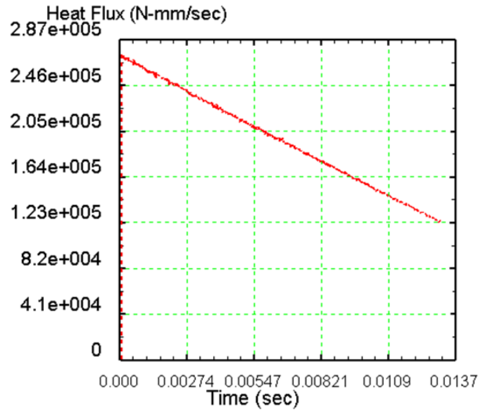
Absorbed power (P) per unit area (A)

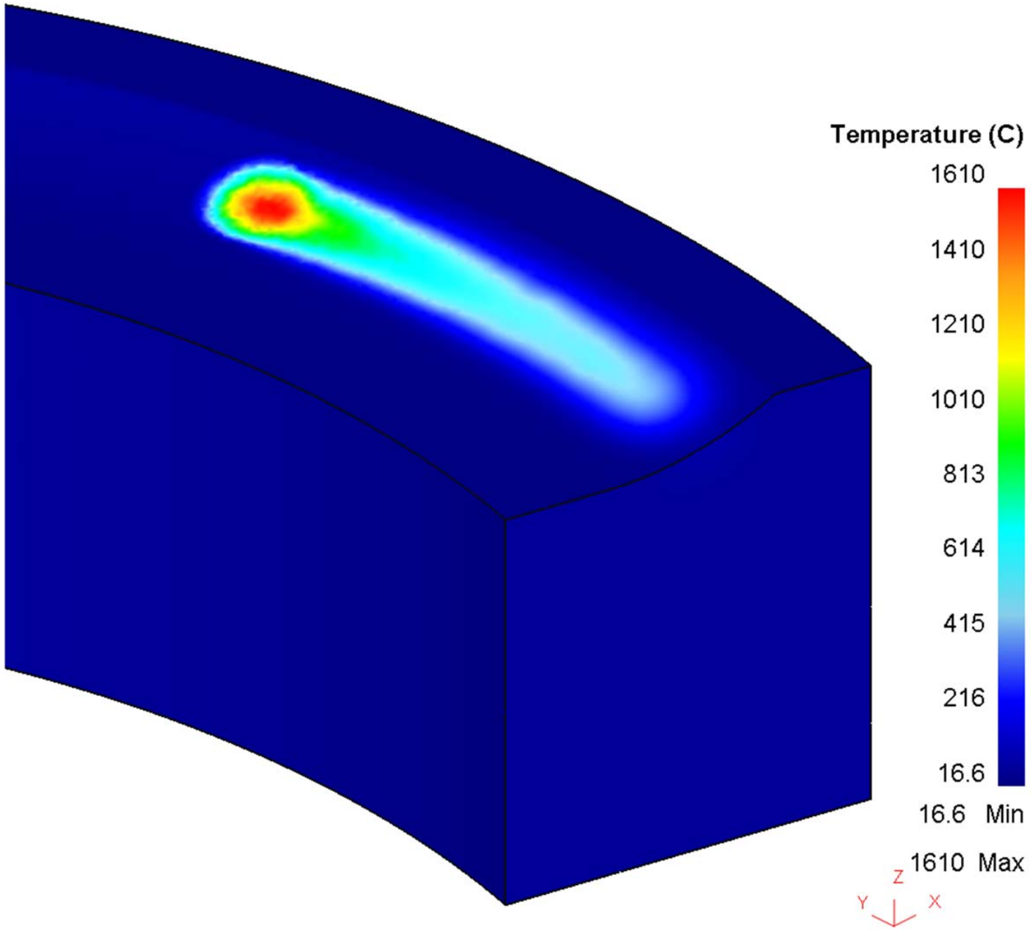
$$P = Ah(T_e - T_s)$$

If the local convection coefficient (h) approaches near zero, the laser power density ($I = P/A$):

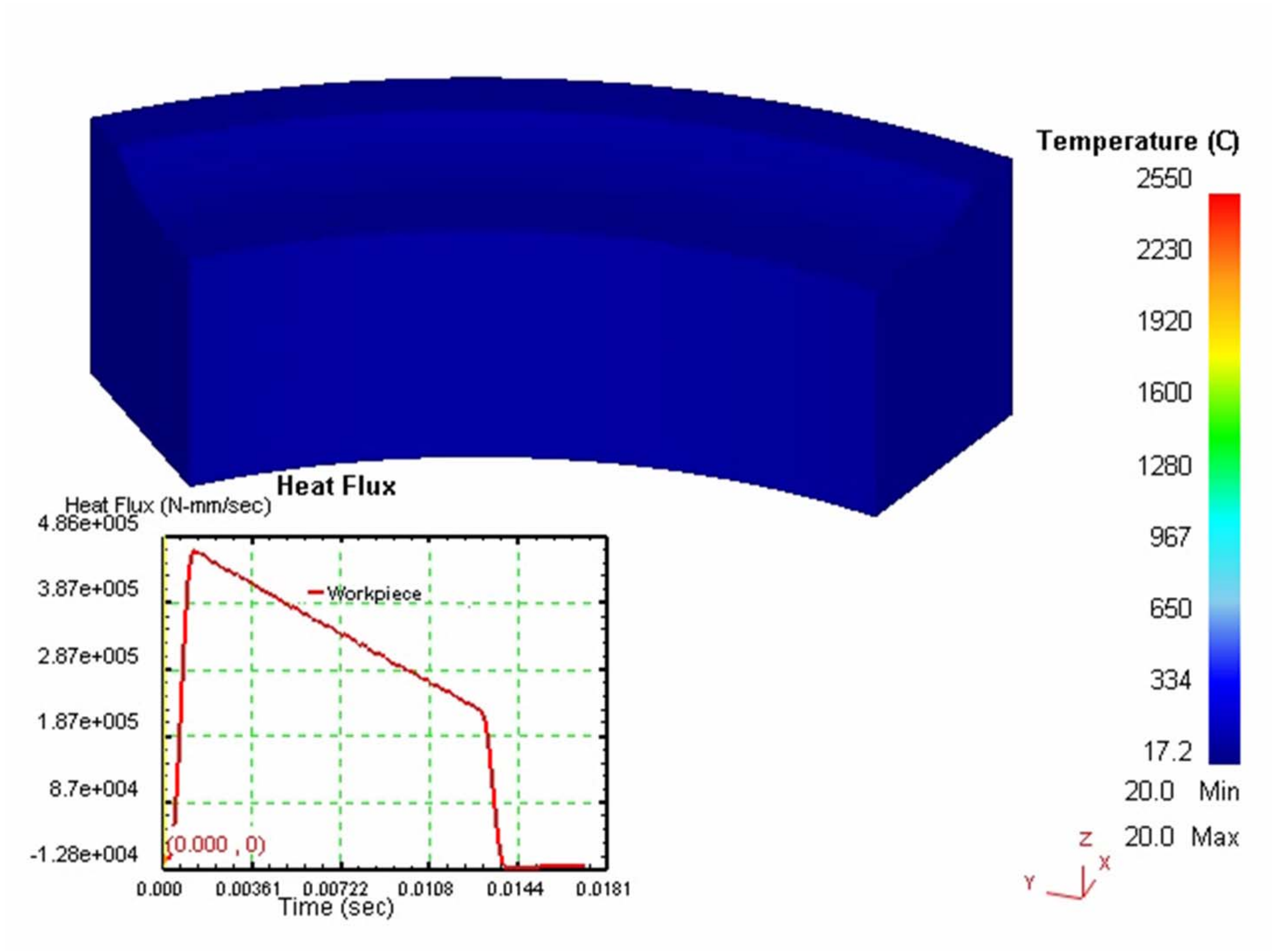
$$I \cong hT_e$$

T_e: environmental temperature
T_s: surface temperature

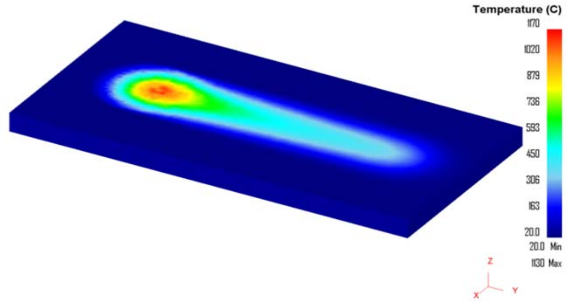


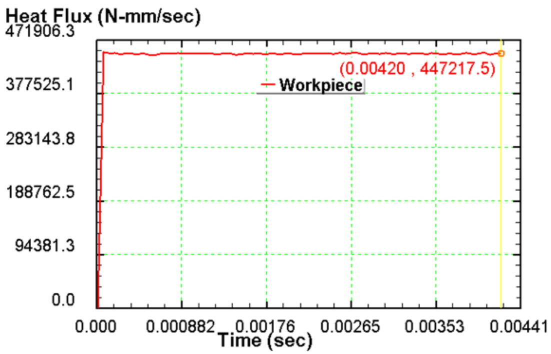


Time Depending Laser Power (Video)

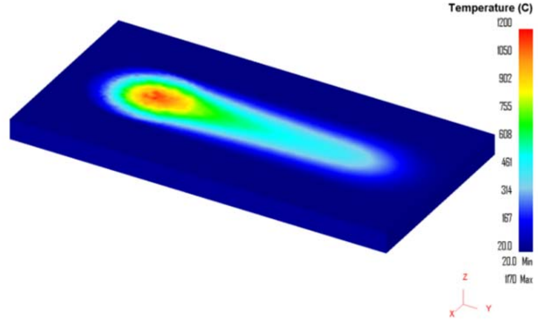


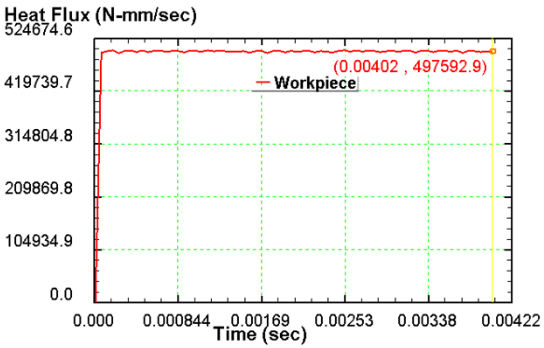
The Modeling of Incident Angle



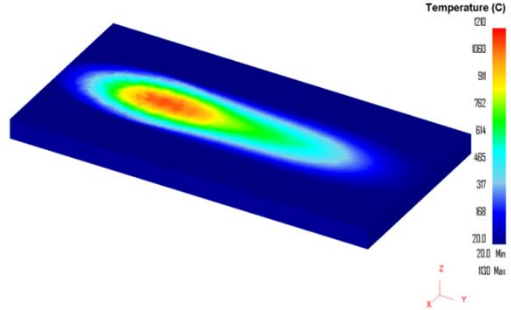


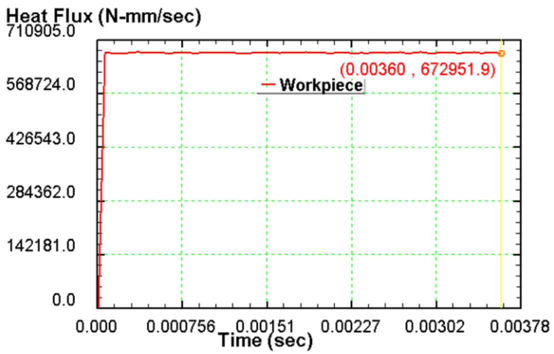
V=100 m/min
Incident angle= 0 °
Power = 1000 W
A_p=0.44





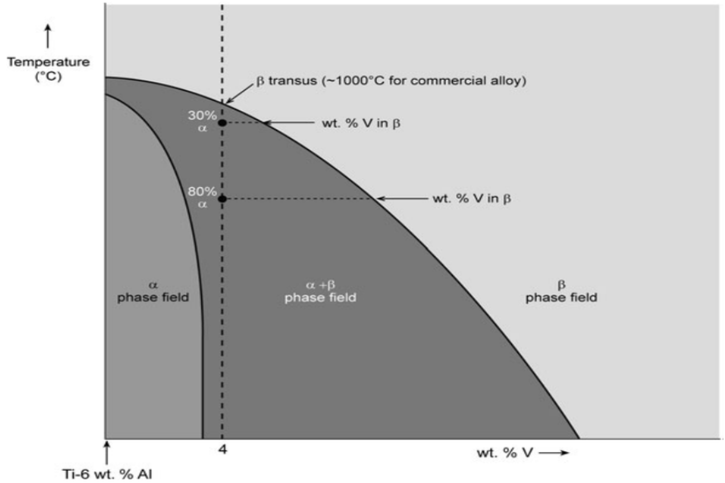
V=100 m/min
Incident angle= 30 °
Power = 1000 W
A_p=0.49

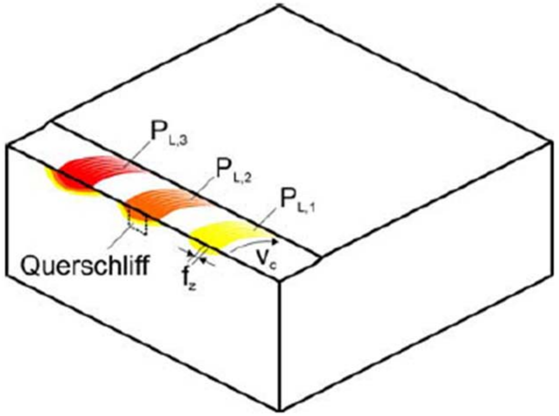


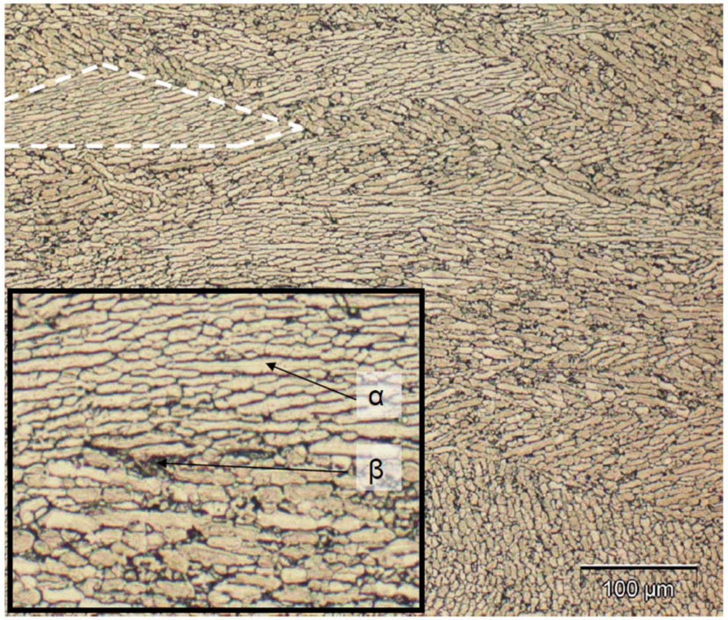


V=100 m/min
Incident angle= 60 °
Power = 1000 W
A_p=0.67

Absorption Coefficient



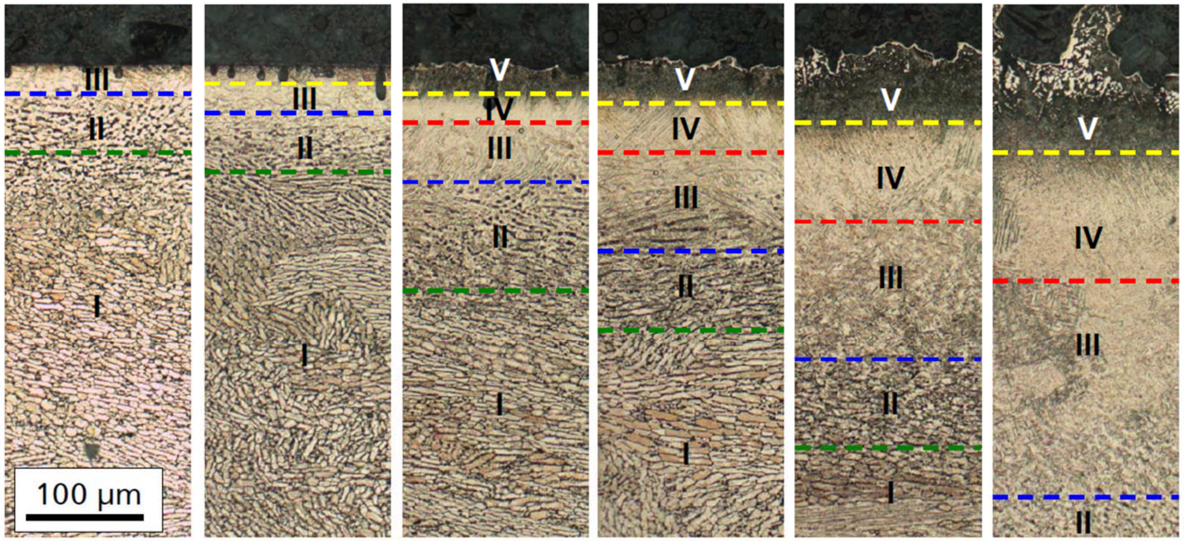




Approach:

- Irradiation of ***Ti-6Al-4V*** workpiece without tool engagement at different laser powers
- Cutting velocity: 25 m/min (331 rpm)
- Feed=50 µm/rev
- Determination of max. temperature by means of depth and kind of microstructure

Absorption Coefficient



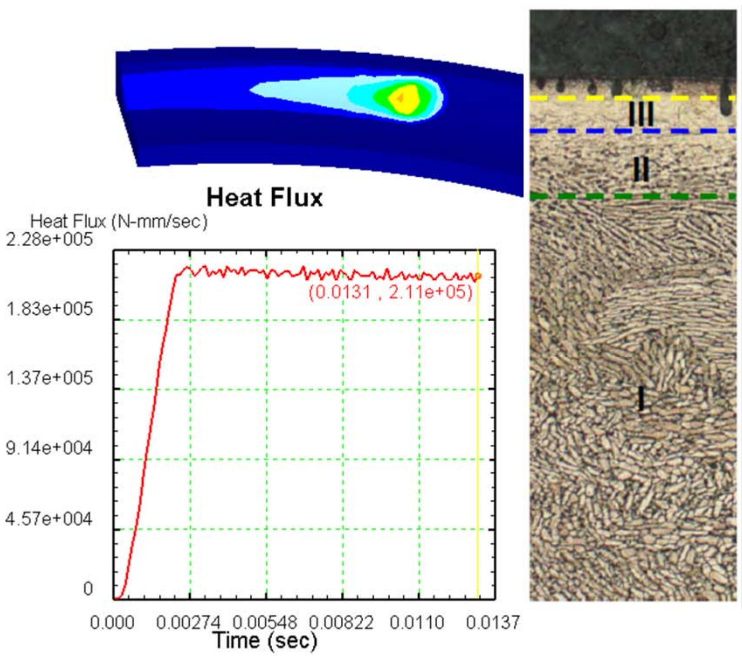
	$P_{L,eff}$ = 893 W	$P_{L,eff}$ = 1071 W	$P_{L,eff}$ = 1250 W	$P_{L,eff}$ = 1428 W	$P_{L,eff}$ = 1607 W	$P_{L,eff}$ = 1785 W
T_{β}	0 µm	0 µm	51 µm	76 µm	136 µm	186 µm
T_{MS}	17 µm	42 µm	102 µm	161 µm	254 µm	373 µm

Estimated absorption coefficient (α):
0.27 ± 0.03

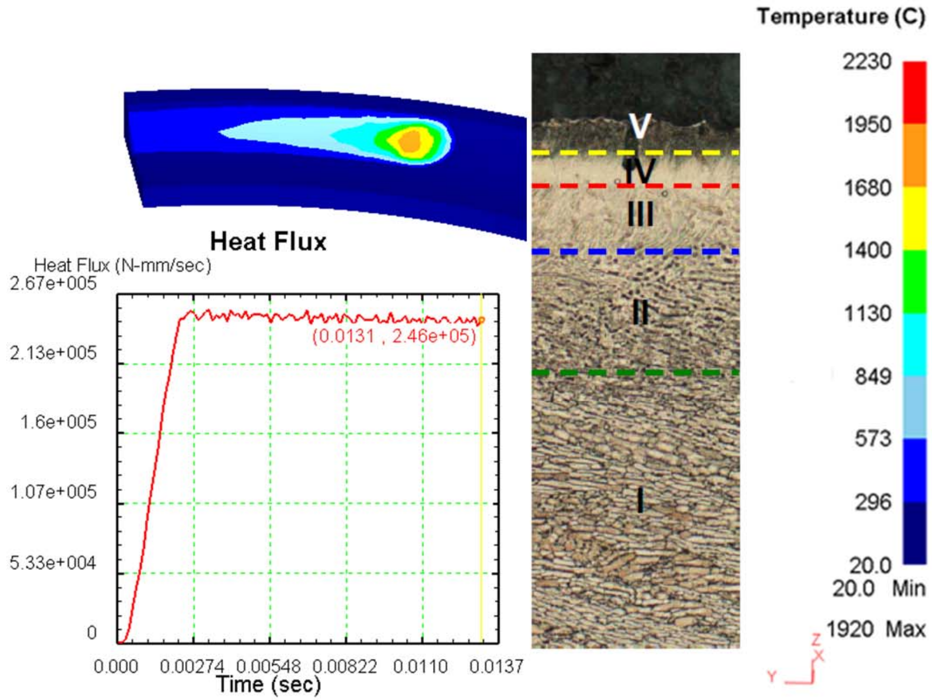
I. initial microstructure (α+β)
II. no martensitic transformation but β transformation from α
III. partial martensitic transformation
IV. complete martensitic transformation
V. oxide layer and white surface layer

Thermal Model Validation

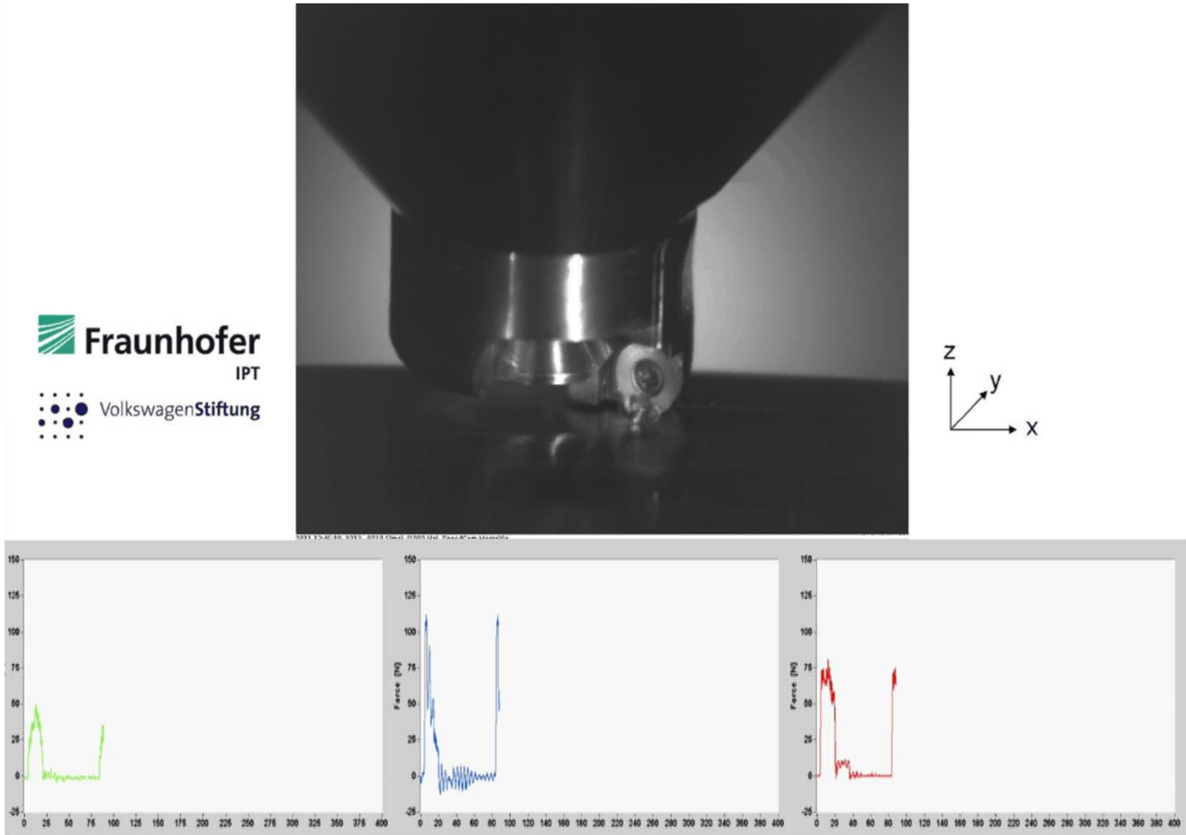
V=25 m/min
Feed=50 µm/rev
Power = 1071 W
α = 0.23



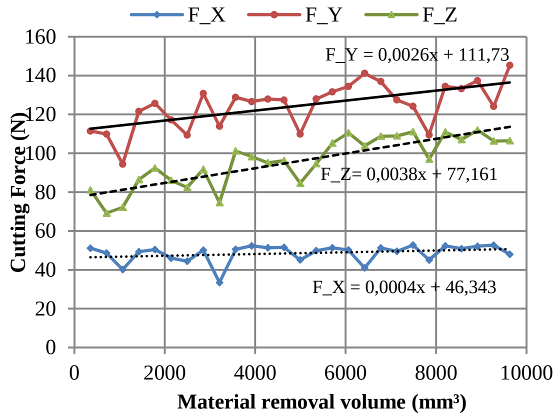
V=25 m/min
Feed=50 µm/rev
Power = 1250 W
α = 0.23

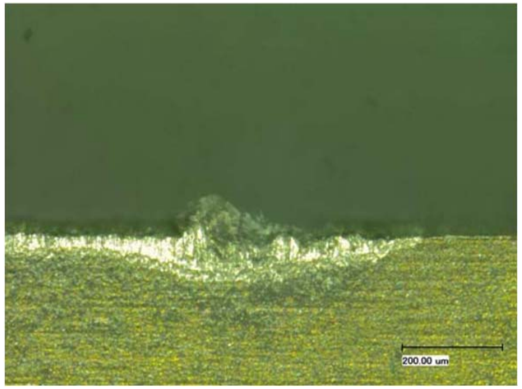


Laser Assisted Milling (Video)

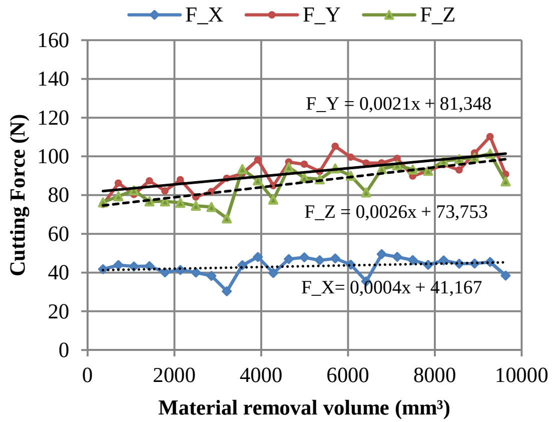


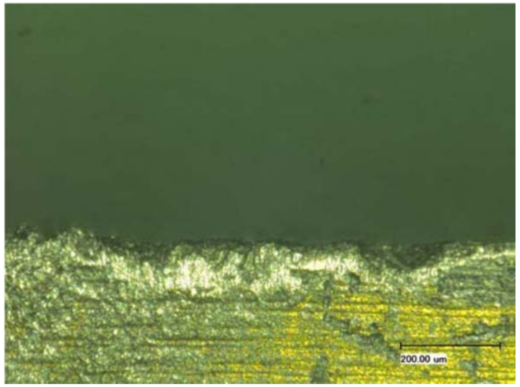
Process Forces and Tool Wear





V=50 m/min
Feed=70 µm/rev
Power = 0 W
Laser advance= 6 mm



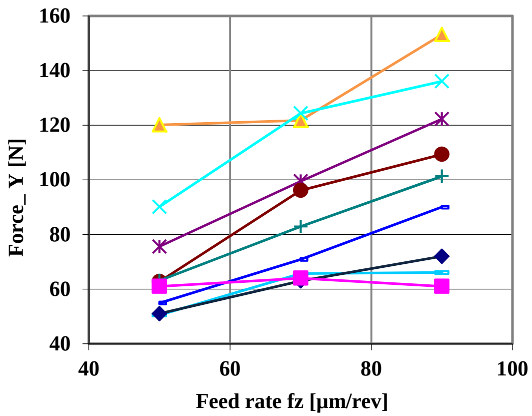


V=50 m/min
Feed=70 µm/rev
Power = 1428 W
Laser advance= 6 mm

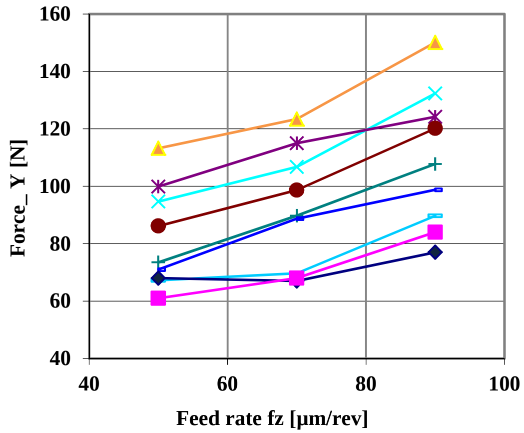
The effect of milling time on the process forces and flank wear

Process Forces

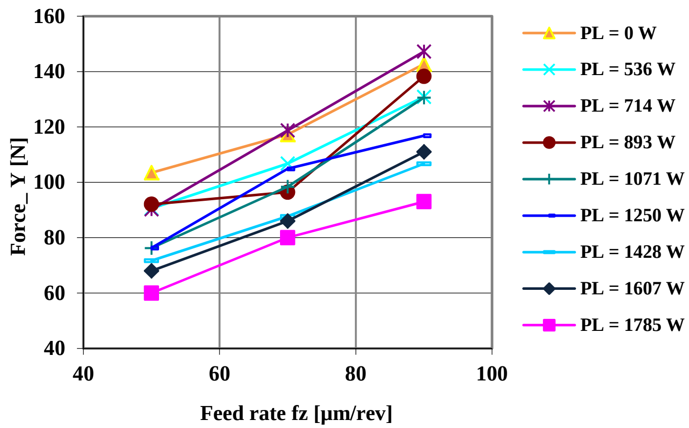
The effect of cutting velocity on the main cutting force at different laser powers



cutting velocity
25 m/min



cutting velocity
50 m/min

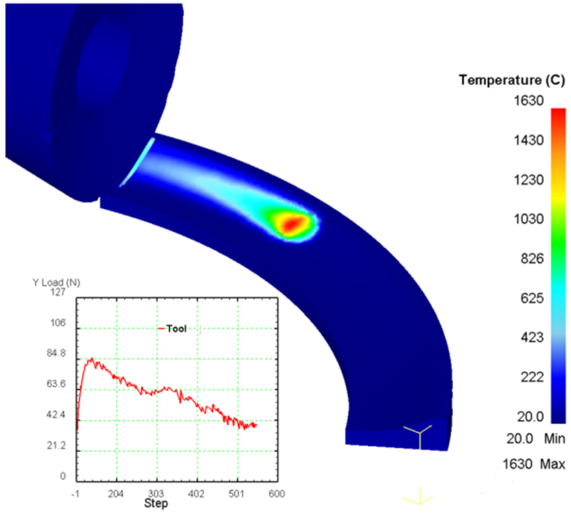


cutting velocity
100 m/min

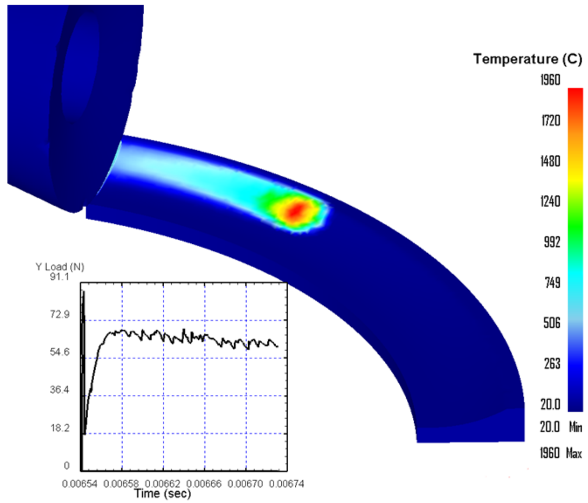
Absolute value of force reduction decreases with cutting velocity

3D FEM of Laser Assisted Milling

Material	Conductivity (W/mK)	Part (Ti6Al4V)	25 °C	7
			500°C	12.6
			900°C	20.2
			995°C	19.3
			1100 °C	21
			1650°C	28.4
		Tool (TiAlN-coated cemented carbide)	25°C	12
			1000°C	20
	heat capacity (J/Kg °C)	Part (Ti6Al4V)	25°C	546
			500°C	651
			900°C	734
			995°C	641
			1100°C	660
			1650 °C	759
		Tool (TiAlN-coated cemented carbide)	598	
Contact area	heat transfer coefficient (kW/m²K)		50	
	Friction coefficient		$m = 0.7$ $\mu = 0.5$	
Environment	Forced convection (Air jet cooling, Overhead) (W/m²K)		2000	
Milling condition	Cutter		RDHX 0702 MOT	
	Cutting width(mm)		8	
	Rake angle (°)		11	
	Nose radius(mm)		0.02	
	Depth of cut (mm)		0.5	
	Cutting velocity(m/min)		25, 50, 75, 100	
	Feed (mm/rev)		0.05, 0.07, 0.09	
	Laser power (W)		536, 714, 893, 1071, 1250, 1428	



Video

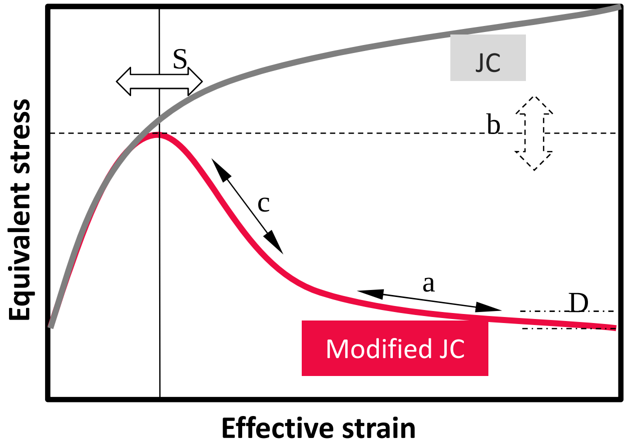


3D FEM of Laser Assisted Milling

Modified (TANH) Johnson- Cook

$$\sigma_{eq} = \left(A + \frac{B\varepsilon^n}{\exp(\varepsilon^a)}\right)\left(1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)\left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right)\left(D + (1 - D)\left[\tanh\left(\frac{1}{(\varepsilon + S)^c}\right)\right]^e\right)$$

$$D = 1 - \left(\frac{T}{T_m}\right)^d \qquad p = \left(\frac{T}{T_m}\right)^b$$

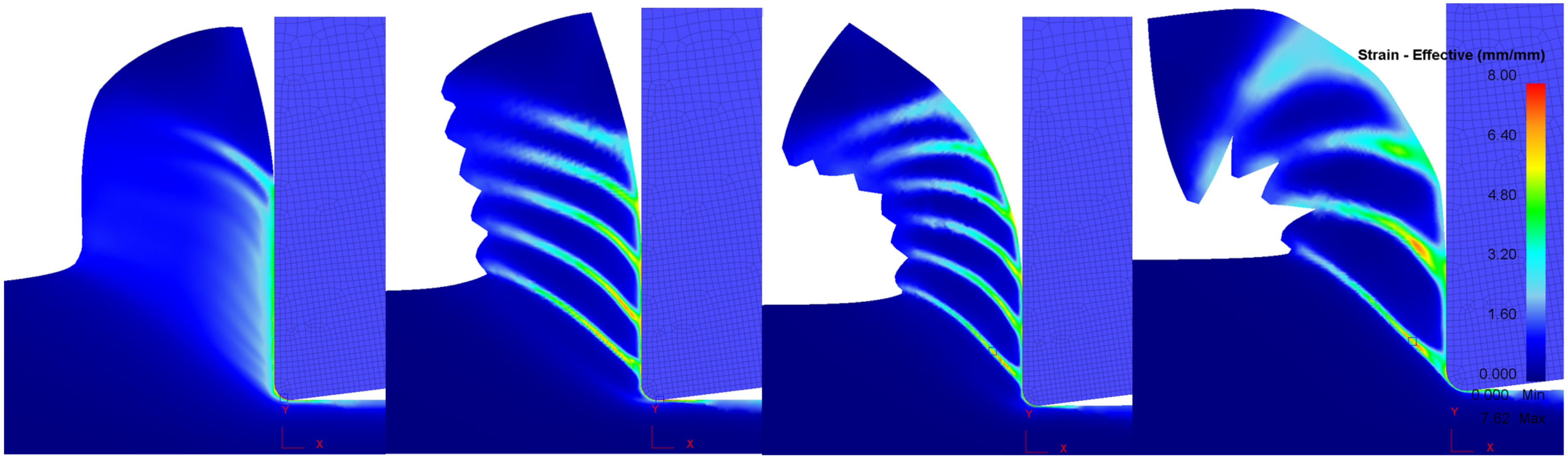


Johnson- Cook

$$\sigma_{eq} = (A + B\varepsilon^n)\left(1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)\left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right)$$

	A (MPa)	B (MPa)	C	m	n	T_m (°C)	a	b	c	d	e
Modified JC-model [Sima et al ,2010]	724	683.2	0.035	1.0	0.47	1660	2	1	2	1	0.05

2D Chip Formation



V=0.005 m/s
Feed=100 µm/rev
Rake angle= 0 °
Power = 0 W

V=0.05 m/s
Feed=100 µm/rev
Rake angle= 0 °
Power = 0 W

V=0.5 m/s
Feed=100 µm/rev
Rake angle= 0 °
Power = 0 W

V=5 m/s
Feed=100 µm/rev
Rake angle= 0 °
Power = 0 W

Nonlinear Thermal Softening (NTS)

Johnson- Cook

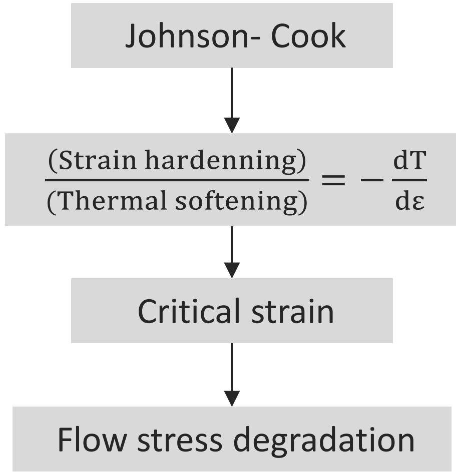
$$\sigma_{eq} = (A + B\varepsilon^n)\left(1 + C\ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right)\left(1 - \left(\frac{T - T_r}{T_m - T_r}\right)^m\right)$$

Minimum strain rate ($\dot{\varepsilon}_c$) for occurrence of adiabatic shear (a simplification for 3D modeling)

$$\dot{\varepsilon}_c = \frac{-\dot{\alpha} n k(T)}{R^2\left(\partial\sigma/\partial T\right)_{\varepsilon,\dot{\varepsilon}}}$$

Nonlinear thermal softening at high strain rates

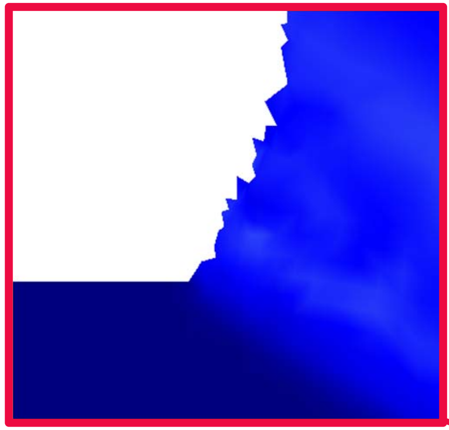
$$m = m_0 \exp\left(-aT^b\right)$$

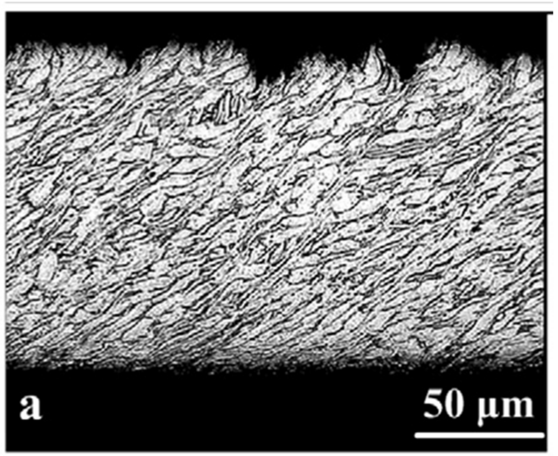


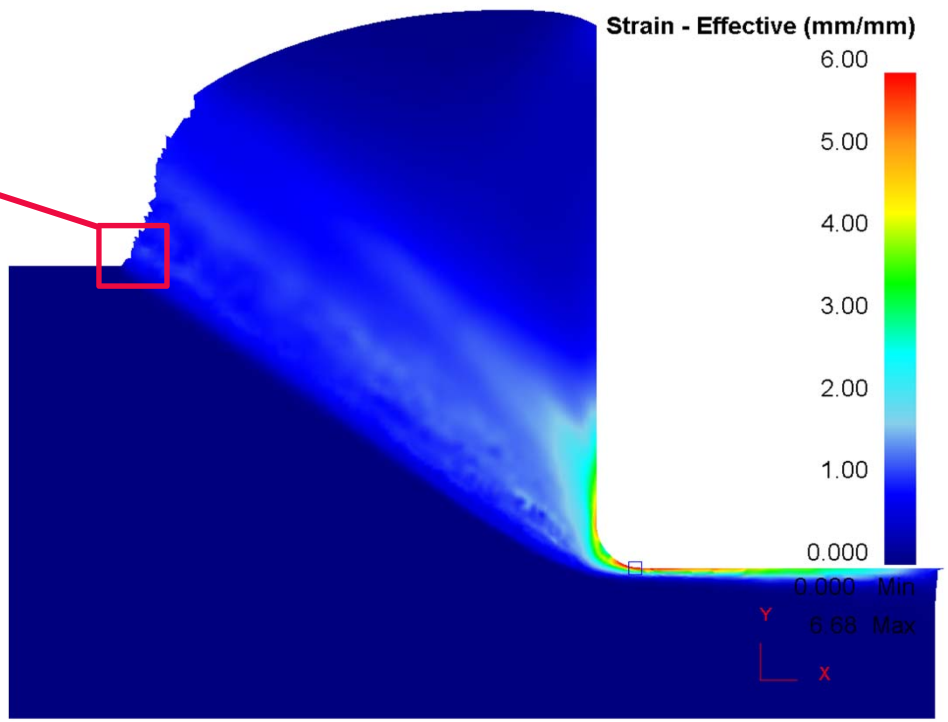
	A (MPa)	B (MPa)	C	m	n	T_m (°C)	a	b	m_0	$\dot{\alpha}$
Modified JC-model	724	683.2	0.035	1.0	0.47	1660	10^{-7}	2.9	1	10^{-4}

2D Chip Formation (NTS)

V=0.05 m/s
Feed=100 µm/rev
Rake angle= 0 °
Power = 0 W

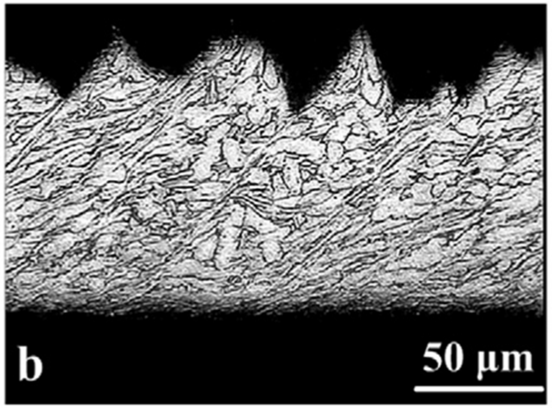


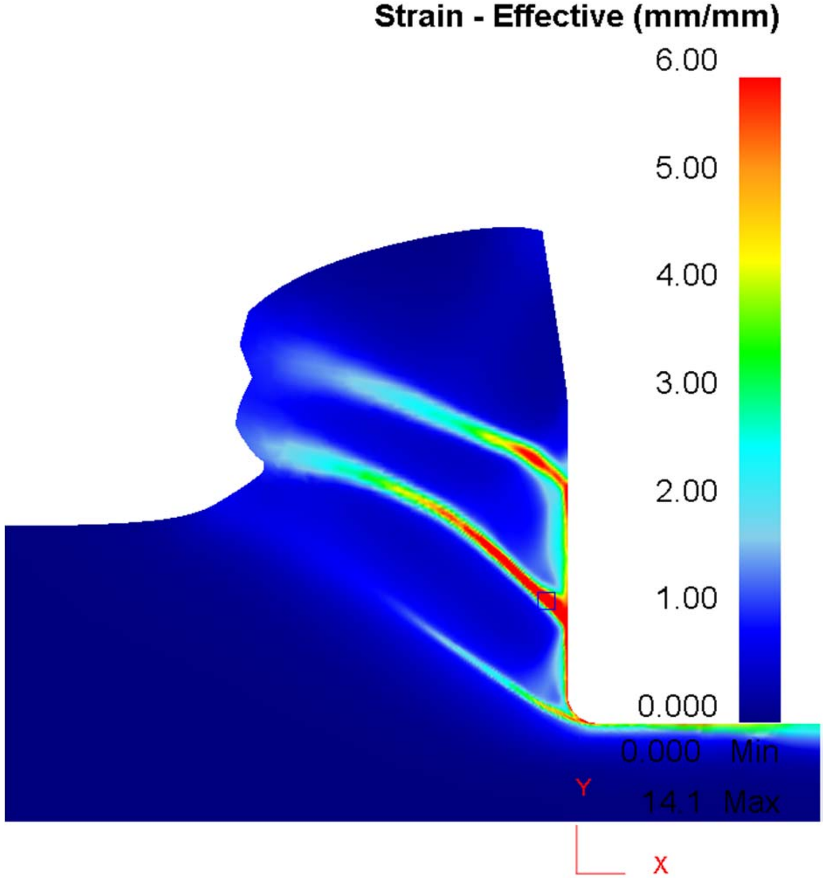




2D Chip Formation (NTS)

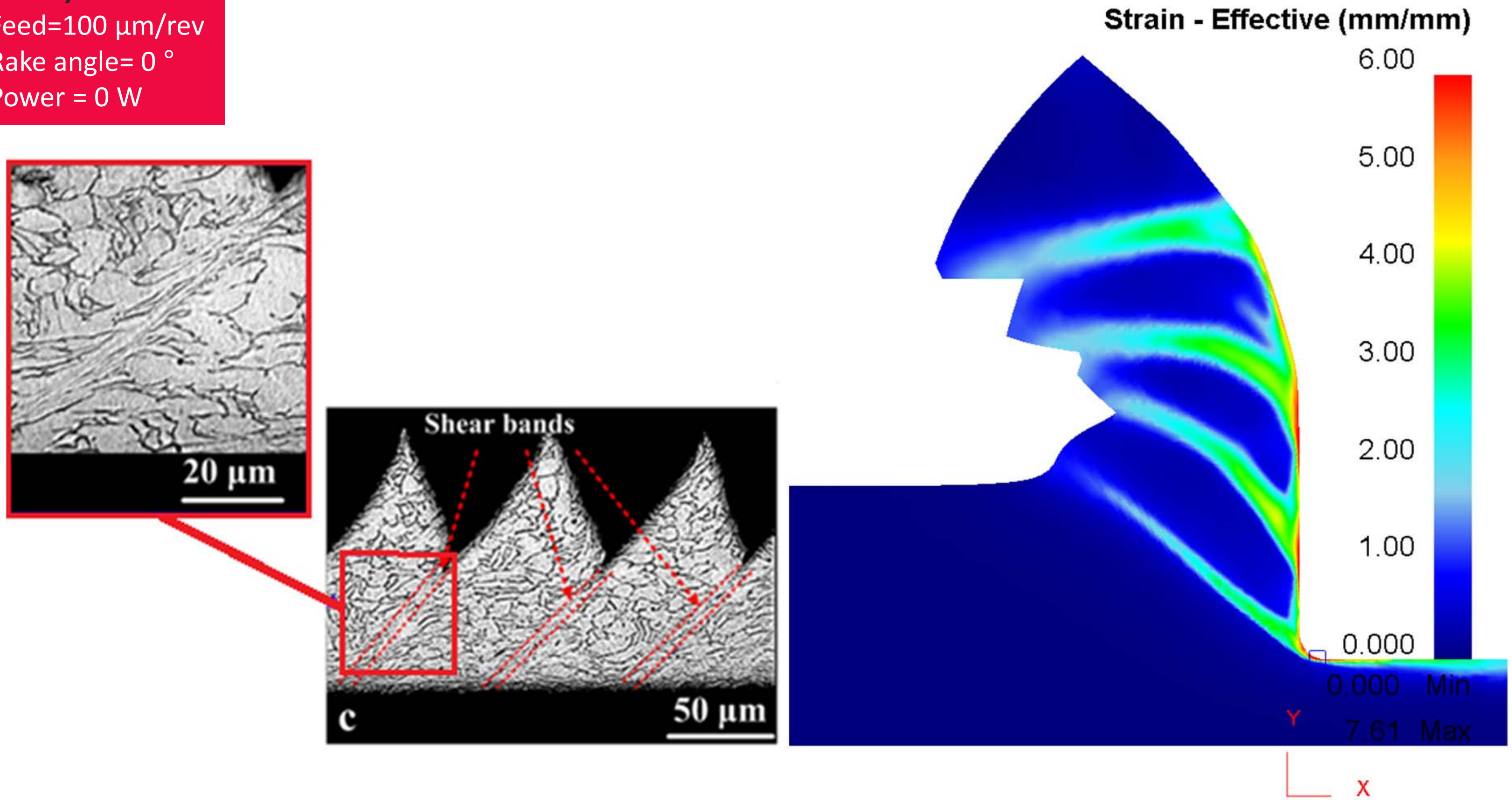
V=0.5 m/s
Feed=100 µm/rev
Rake angle= 0 °
Power = 0 W





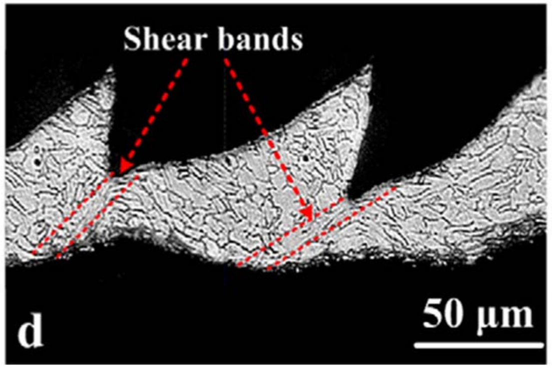
2D Chip Formation (NTS)

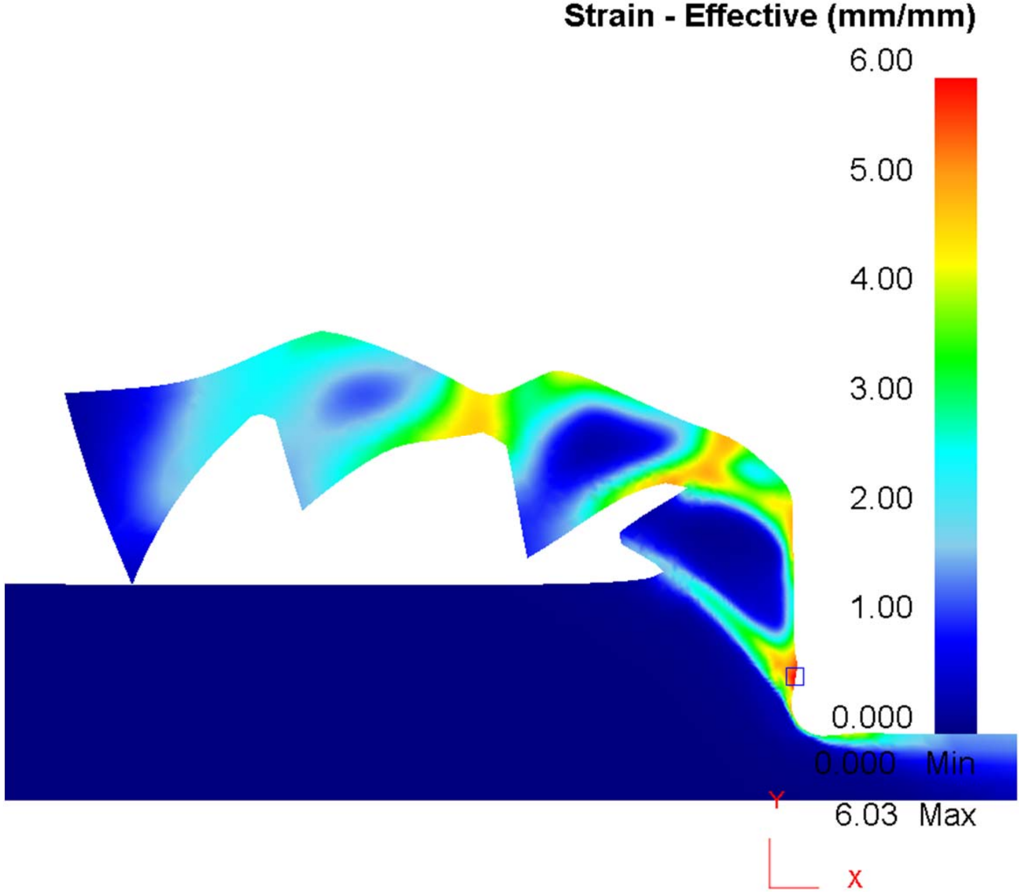
V=5 m/s
Feed=100 µm/rev
Rake angle= 0 °
Power = 0 W



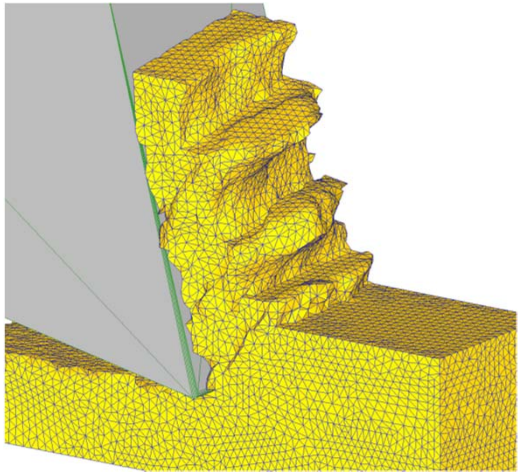
2D Chip Formation (NTS)

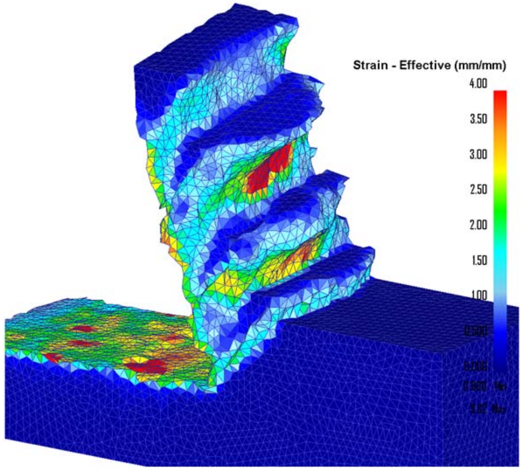
V=312 m/s
Feed=100 µm/rev
Rake angle= 0 °
Power = 0 W

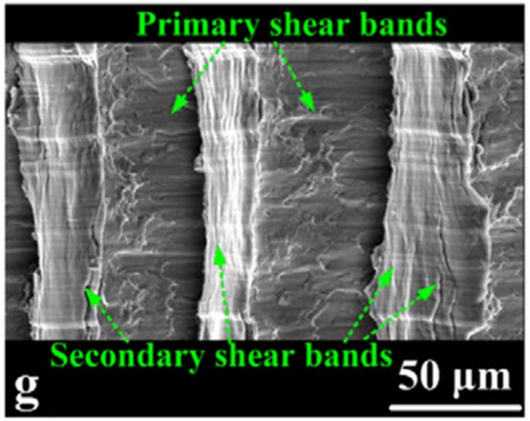




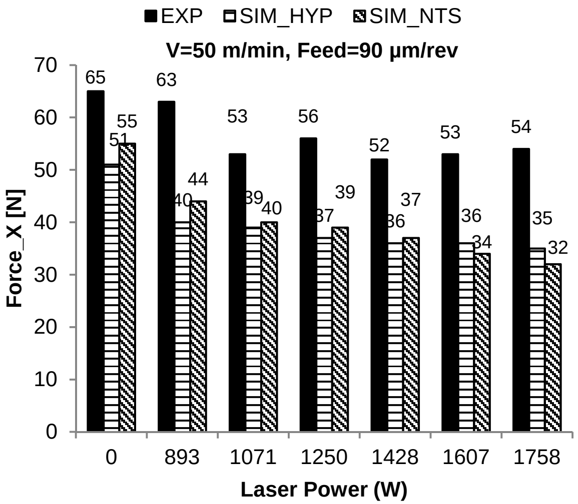
3D Chip Formation (NTS)

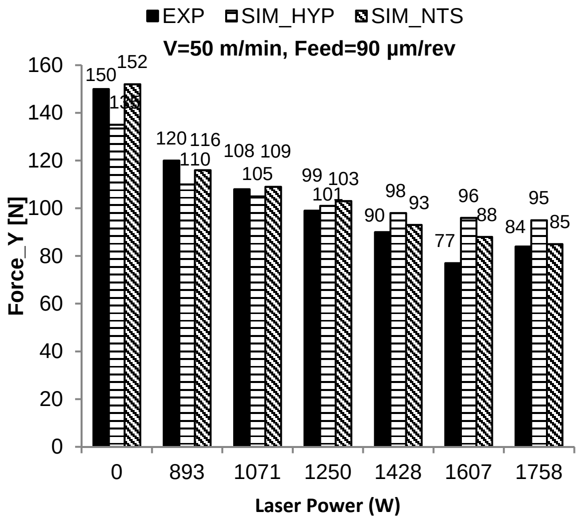


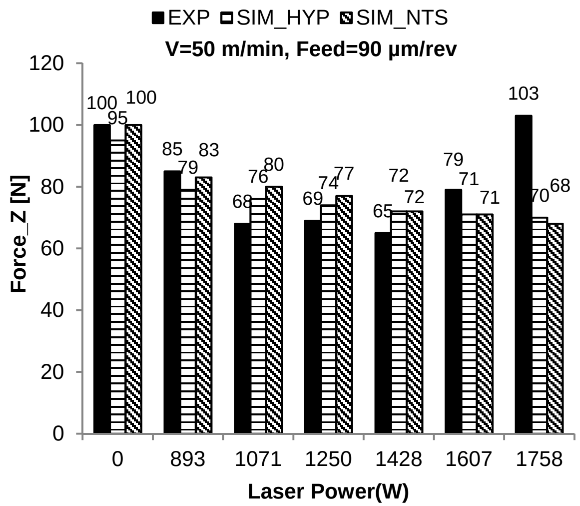




3D Model validation







- The amount of predicted force reduction with increasing the laser power in X direction is higher than the experimental results
- An excellent agreement for cutting forces in Y-direction was found for the used model
- The forces in Z-direction showed a very good agreement for laser powers up to 1428W

Summary

Review:

- Presentation of novel laser assisted milling
- Results of laser-assisted milling of Ti-6Al-4V using TiAlN-coated cemented carbide cutting insert in different cutting conditions
- Reduction of force in X-direction up to 25%, Y-direction up to 60% and Z-direction up to 65%
- Low level of tool wear according to the milling time
- 3D-FEM simulation
- Integration of time depending laser power in machining simulation
- Model validation for machining of Ti6Al4V at different cutting conditions (TANH and NTS)

Outlook:

- Expand the milling material spectrum
- Increasing the machining productivity

Acknowledgements

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Thanks for your attention