Micro Milling of Additive Manufactured Metals
A Machinability Analysis

Prof. Dr.-Ing. habil Dr.-Ing. E.h. E. Brinksmeier
Dr.-Ing. O. Riemer
M.Sc. K. Kempen
Dipl.-Ing. C. Brandao

1 Uni Bremen, Laboratory for Precision Machining LFM, Germany
2 KU Leuven, Dept. of Mechanical Engineering, Belgium
Hi-Micro Project – Main Goals

- Innovative process chain for micro injection moulding parts
- Monolithic tool inserts with cooling channels using additive manufacturing
- Post processing of tool insert features (i.e. by micro milling)
- Micro parts for various applications:
  - micro fluidics
  - mechanical parts
  - optical parts

Source: kurzweil, sophion, officine panerai, optogenetics
Outline

- Novel process chain for injection mould manufacturing with internal cooling channels
- Additive manufactured materials
- Micro milling
  - Machined features
  - Milling Parameters
- Results
  - Surface quality
  - Shape accuracy
- Conclusion
Process Chain for Mould Manufacturing
for Moulds with Cooling Channels

- Mould design
- Mould making
- Injection moulding
- Micro part

Additive manufacturing
- Cooling channels
- Raw insert with cooling channels
- Insert with structured micro cavity
- Variotherm micro moulding
- High quality precise micro parts

IWT
Institut für Werkstofftechnik
Bremen

ECO Centrum

LFM
Labor für Mikrozerspanung
Additive Manufacturing: Selective Laser Melting

Additive manufacturing:
by layer-wise addition of material,
rather than by material removal (e.g. drilling, milling, grinding, EDM …) or forming (e.g. forging, deep drawing, moulding, …)
Maraging steel X3NiCoMoTi 18-9-5 (1.2709)
- Density ≈ 100%
- Hardness 33 – 37 HRC (330 – 370 HV)\(^1\)
- Tensile strength 1100 MPa (conv.: 950 – 1100 MPa)
- Surface roughness Sa 4 – 6.5 µm

Aluminium alloy AlSi10Mg (3.2381)\(^2\)
- Density 98 – 99%
- Hardness ≈ 127 HV (conv.: 86 HV)
- Tensile strength ≈ 390 MPa (conv.: 310 MPa)
- Surface roughness Sa 7 – 10 µm

\(^1\) DIN EN ISO 18265:2002
\(^2\) K. Kempen et al. Mechanical properties of AlSi10Mg Produced by Selective Laser Melting, Physics Procedia 39 (2012)
Micro Milled Features

- **Ribs / thin walls (continuous)**
  - Aspect ratio: 1 – 10
  - Constant height: 0.3 mm
  - Variable width: 0.3, 0.15, 0.05, 0.03 mm

- **Grooves (continuous)**
  - Aspect ratio: 1 – 1.5
  - Variable depth: 0.3, 0.2, 0.15 mm
  - Variable width: 0.3, 0.2, 0.1 mm

- **Pocket (discontinuous)**
  - Aspect ratio: 0.05
  - Constant width (2 mm) and depth (0.1 mm)
Milling Conditions
Standard Cutting Parameters and Feed Rate Variation

➤ Micro end mills

- Torus / WC, TiAlN coated / d = 0.5 mm
- Flat-end / WC / d = 0.2, 0.1 and 0.08 mm
- Ball-end / WC, TiAlN coated / d = 0.5 mm

➤ Cutting parameters (as recommended)

- Width of cut \( a_e \): 5 – 50 µm
- Depth of cut \( a_p \): 5 – 50 µm
- Feed velocity \( v_f \): 60 – 80 mm/min
  400 – 1,000 mm/min
- Cutting velocity \( v_c \): 10 – 26 m/min
  65 m/min
Thin Walls – Surface Analysis

Process
Down milling

Material
Steel (1.2709)
Aluminium (3.2381)

Tool
Torus-end mill,
WC, TiAlN, d0.5 mm

Parameters
\( a_e = 50 \, \mu m \)
\( a_p = 50 \, \mu m \)
\( v_c = 20.5 \, m/min \)

Metrology
White light interferometry

Graph: Roughness \( S_a \) vs. Feed velocity \( v_f \) [mm/min]
- Aluminium
- Steel

Legend:
- Green line: Aluminium
- Blue line: Steel

Graph data:
- Roughness \( S_a \) in nm
- Feed velocity \( v_f \) in [mm/min]

Scale:
- Roughness \( S_a \) range: 50 to 250 nm
- Feed velocity \( v_f \) range: 400 to 600 [mm/min]
Thin Walls - Shape Analysis

- **Process**
  - Down milling

- **Material**
  - Steel (1.2709)
  - Aluminium (3.2381)

- **Tool**
  - Torus-end mill, WC, TiAlN, d0.5 mm

- **Parameters**
  - $a_e = 50 \, \mu m$
  - $a_p = 50 \, \mu m$
  - $v_c = 20.5 \, m/min$

- **Metrology**
  - Confocal Microscopy
Grooves – Surface Analysis

Process
Down milling

Material
Steel (1.2709)
Aluminium (3.2381)

Tool
Flat-end mill, 
d0.2, 0.1, 0.08 mm
Ball-end mill, d0.5 mm

Parameters

- \( a_e = 5 \, \mu m \)
- \( a_p = 5, 20 \, \mu m \)
- \( v_c = 10 – 63 \, m/min \)

Metrology
White light interfer.
Grooves – Shape Analysis

Process
Down milling

Material
Steel (1.2709)
Aluminium (3.2381)

Tool
Flat-end mill,
d0.2, 0.1, 0.08 mm
Ball-end mill, d0.5 mm

Parameters
\( a_e = 5 \, \mu m \)
\( a_p = 5, 20 \, \mu m \)
\( v_c = 10 – 63 \, \text{m/min} \)

Metrology
Confocal microscopy
Pocket – Shape Analysis

Process
Down milling

Material
Steel (1.2709)
Aluminium (3.2381)

Tool
Flat-end mill,
WC, TiAlN, d0.2 mm

Parameters
$a_e = 5 \, \mu m$
$a_p = 5, 20 \, \mu m$
$v_c = 10 – 63 \, m/min$
$v_f = 80 \, mm/min$

Metrology
Confocal microscopy
Pocket – Surface Analysis

Process
Down milling

Material
Steel (1.2709)
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Tool
Flat-end mill,
WC, TiAlN, d0.2 mm

Parameters
\( a_e = 5 \, \mu m \)
\( a_p = 5, 20 \, \mu m \)
\( v_c = 10 – 63 \, m/min \)
\( v_f = 80 \, mm/min \)

Metrology
White light interfer.

Roughness Sa

Aluminium

Steel
Conclusion

- Surface roughness down to Sa120 nm achievable, but single defects lead to scrap

- Reduction of tool and material deflection by low feed rate

- Maraging steel
  - Lower surface roughness
  - Higher density
  - Higher shape accuracy (general)
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Cooling Channels in Injection Moulds
State of the Art in Variotherm Processes

Injection moulds with cooling channels:
- Faster cooling
- Shorter cycle time
- Less warpage

Micro injection moulds with cooling channels:
- More accurate micro features
- Longer melt flow
- Less warpage

Source: gwk