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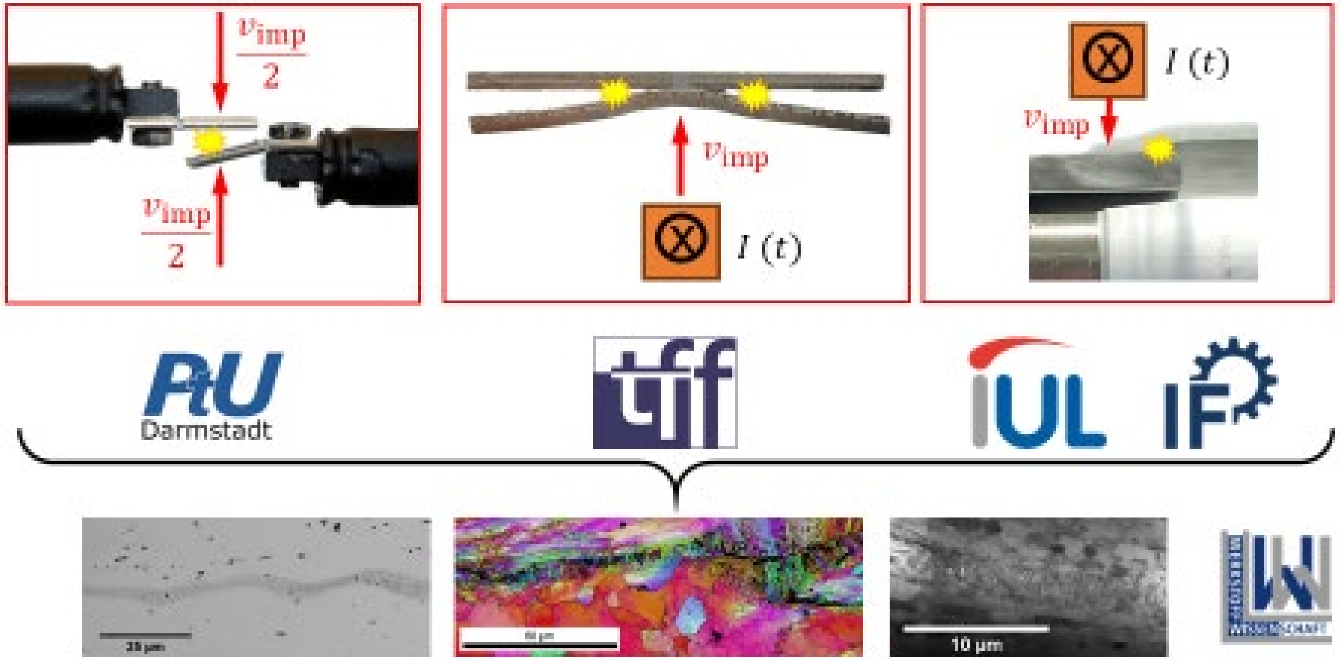
# Particle Ejection by Jetting and Related Effects in Impact Welding Processes
# &
# Interface Formation during Collision Welding of Aluminum

Presentation of the Working Group High-Speed Joining from the Priority Program 1640 „Joining by plastic deformation" at the International Conference on High-Speed Forming ICHSF 2021

15th of October 2021 via Zoom-Meeting

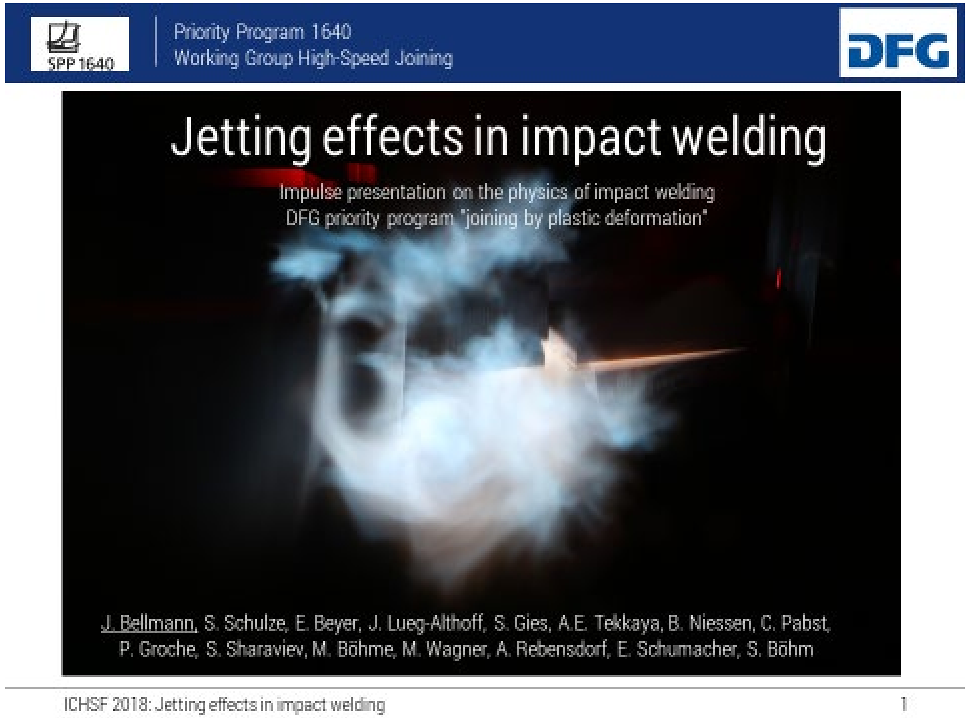
# Historical Background – Part 1

- 2012 – 2019: Priority Program 1640 „Joining by plastic deformation“ (German Research Foundation)
- 2017 – 2020: Inter-institute cooperation for the investigation of the basic mechanisms in collision welding processes “ High-Speed Joining”



# Historical Background – Part 2

- 2018: Conference talk at ICHSF 2018, Ohio
- 2020: Publication of results




metals MDPI

*Article*

**Particle Ejection by Jetting and Related Effects in Impact Welding Processes**

Jörg Bellmann [1,2,*], Jörn Lueg-Althoff [3], Benedikt Niessen [4], Marcus Böhme [5], Eugen Schumacher [6], Eckhard Beyer [1], Christoph Leyens [2,7], A. Erman Tekkaya [3], Peter Groche [4], Martin Franz-Xaver Wagner [5] and Stefan Böhm [6]

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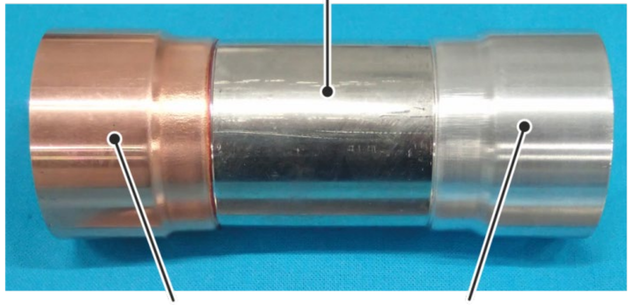
Benedikt Niessen [1,*], Eugen Schumacher [2], Jörn Lueg-Althoff [3], Jörg Bellmann [4,5], Marcus Böhme [6], Stefan Böhm [2], A. Erman Tekkaya [3], Eckhard Beyer [4], Christoph Leyens [5,7], Martin Franz-Xaver Wagner [6] and Peter Groche [1]

# Agenda

1. Principle of impact welding
2. (Some) open questions realted to impact welding
3. Influence of the flyer mass – Experimental setups (#1 and #2) und findings
4. Influence of the temperature – Experimental setups (#3, #4 and #5) und findings
5. Cool application!
6. Conclusion

# 1. Principle of Impact Welding
## Applications and Advantages

Ø36 x 2 mm
1.4541



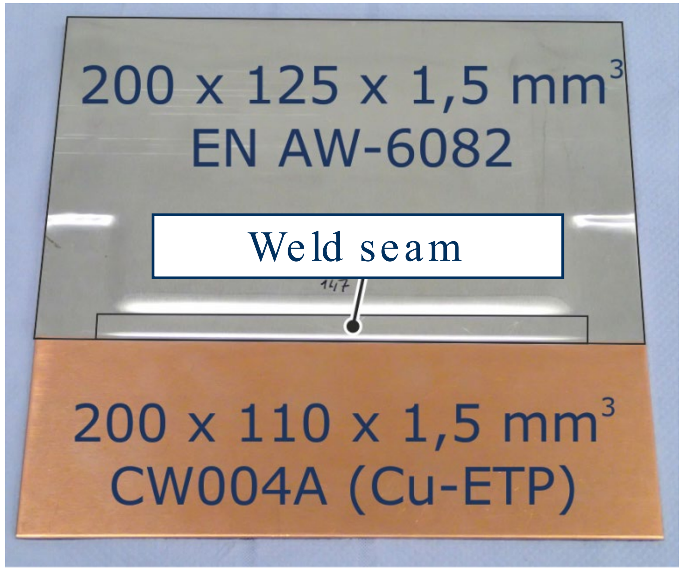
Ø40 x 1 mm
CW004A
(Cu-ETP)

Ø40 x 1 mm
EN AW-1050

[Fraunhofer IWS, 2018]

Ø 5,84 mm
z.B. Inconel 706

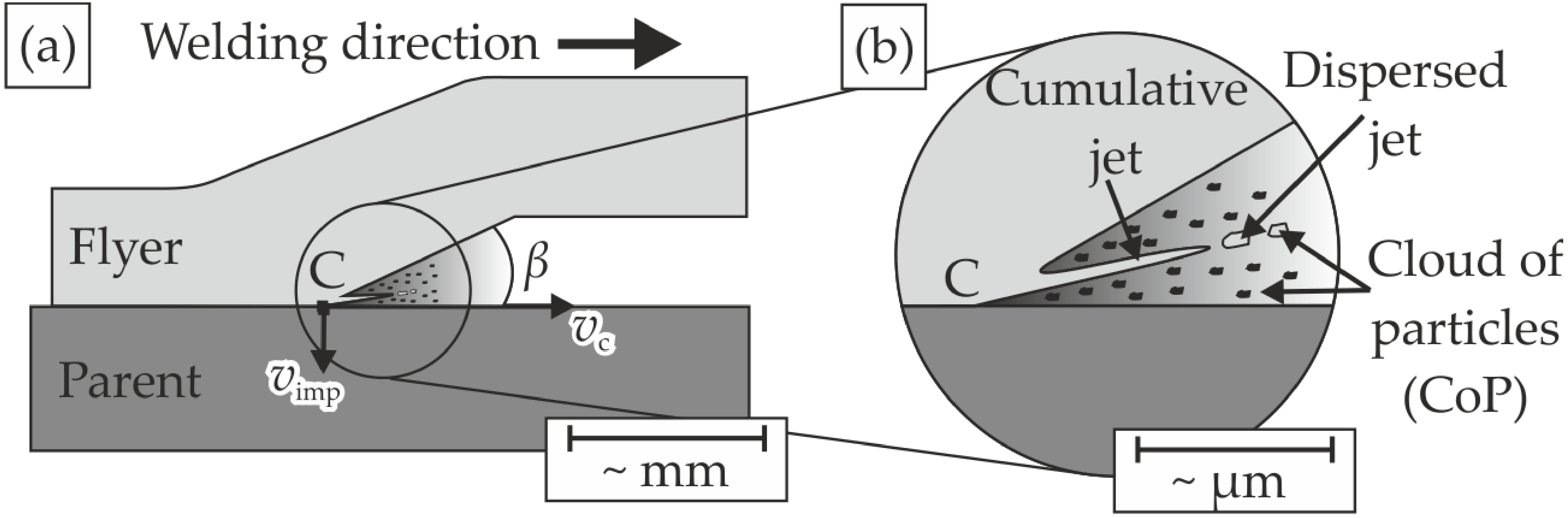
[Magneform, 1978]



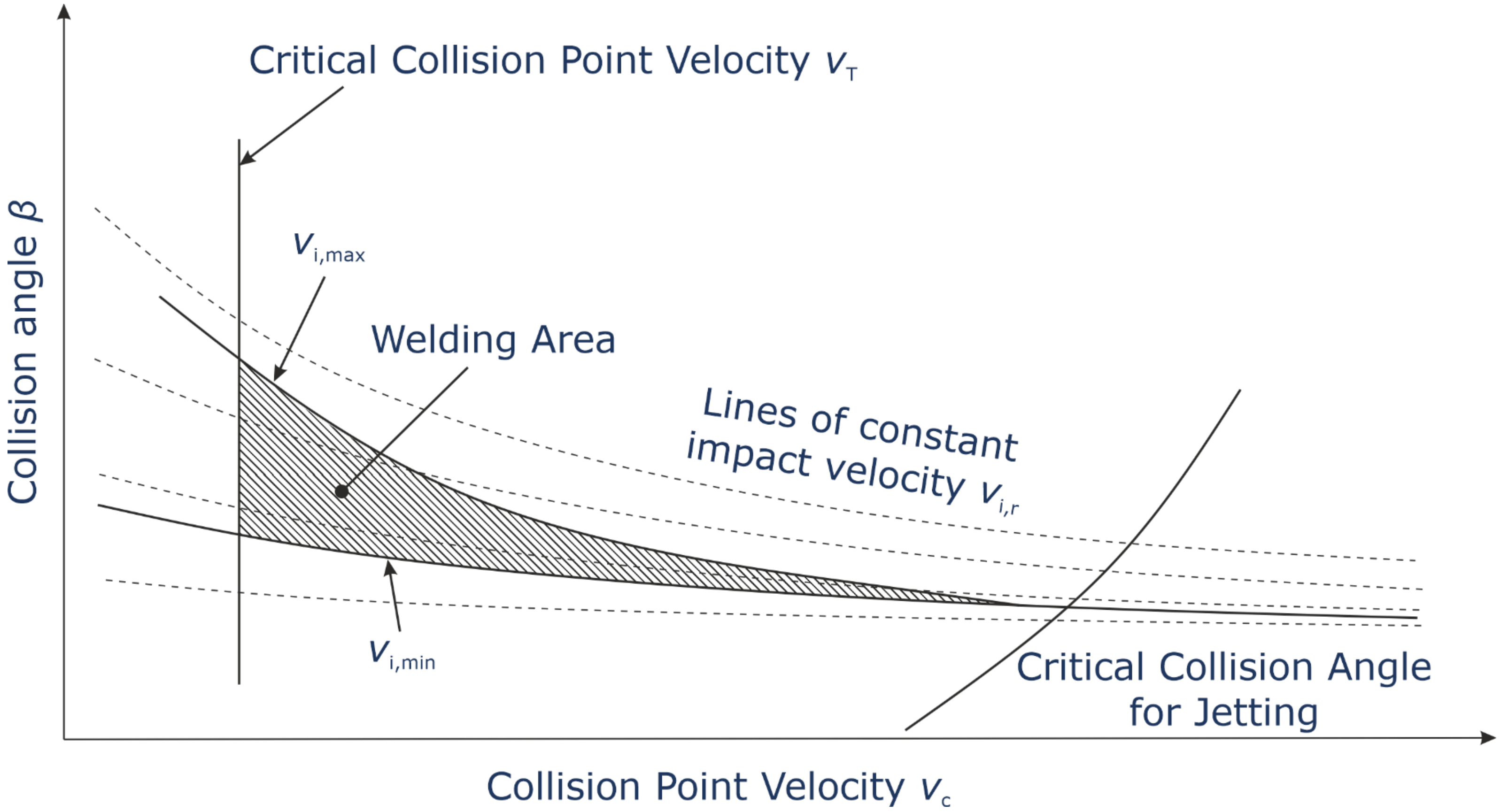

[Fraunhofer IWS, 2018]

- Similar and dissimilar metal welding
- Short process times (µs)
- No need for filler materials
- Applicable for tubular and flat parts

# 1. Principle of Impact Welding
Definitions



# 1. Principle of Impact Welding
## Welding Windows

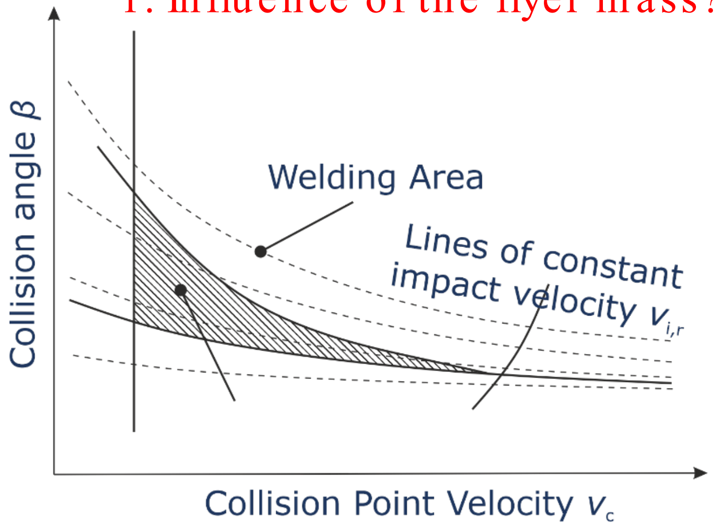



[Carpenter und Wittmann, 1975]

# 2. (Some) Open Questions Related to Impact Welding

1. Is there an effect of the flyer mass and the kinetic flyer energy, respectively, on the welding mechanism and the welding result?
2. Is it allowed to neglect the temperature-based effects in the welding gap before contact?

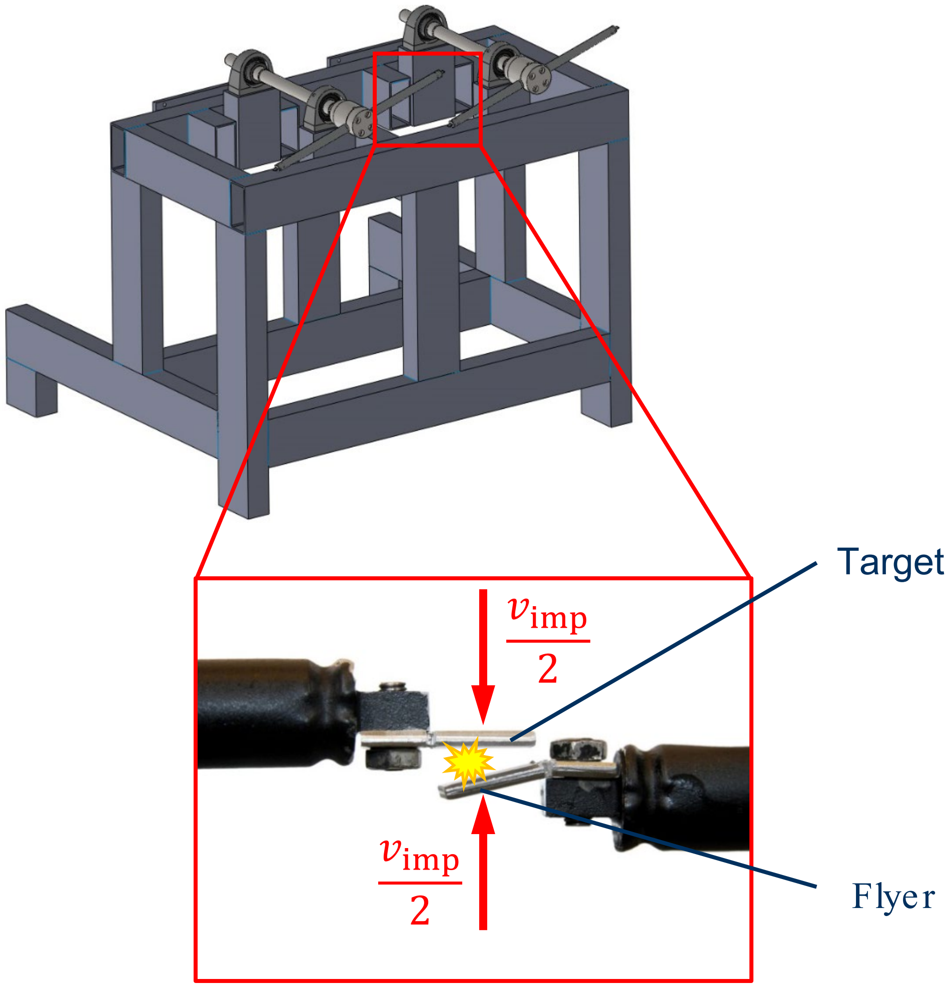
1. Influence of the flyer mass?

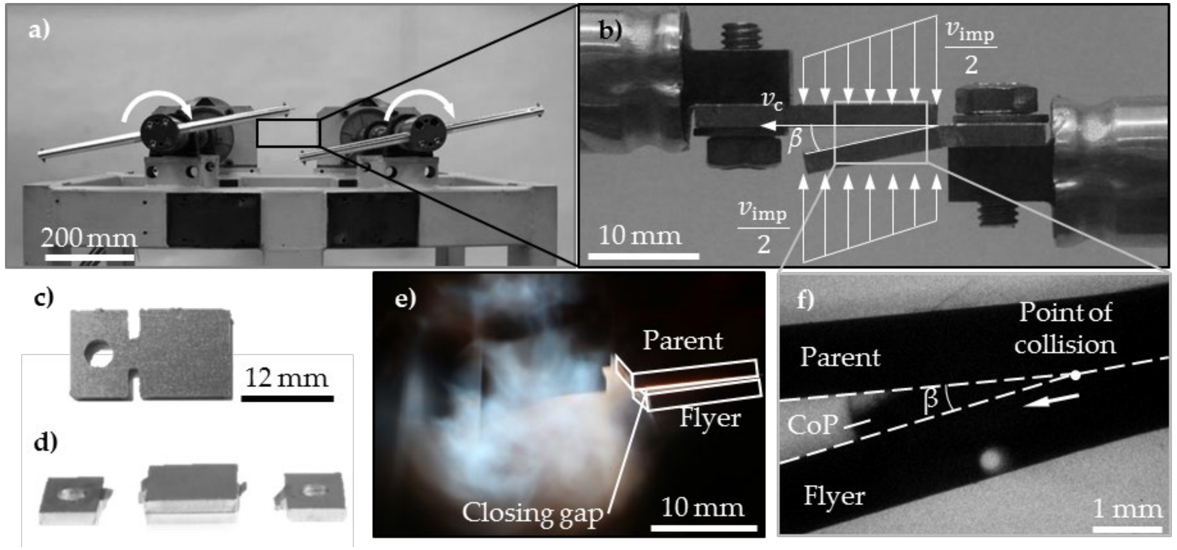



2. Influence of the temperature?

# 3. Influence of the flyer mass

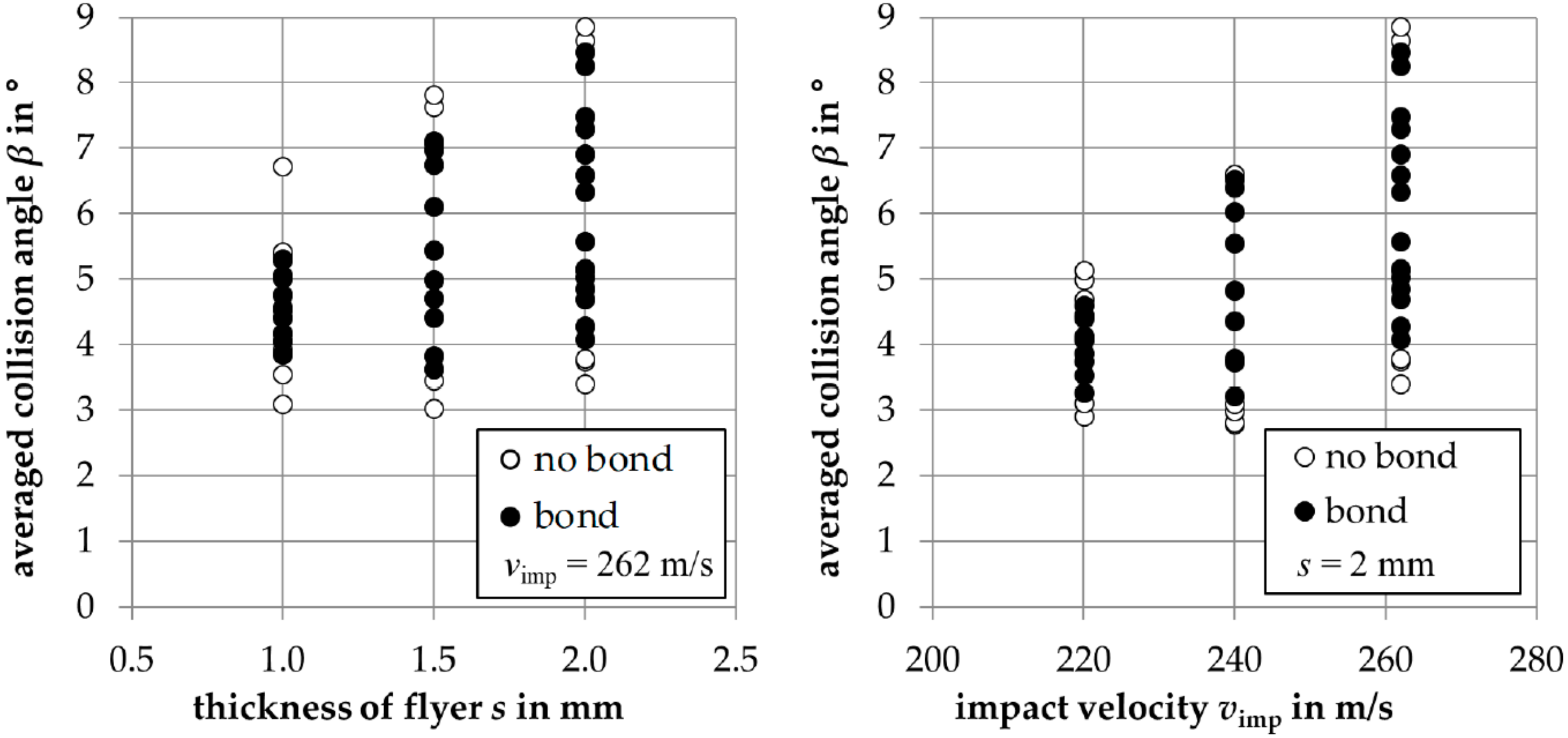
## Experimental Setup (#1 - Model test rig)



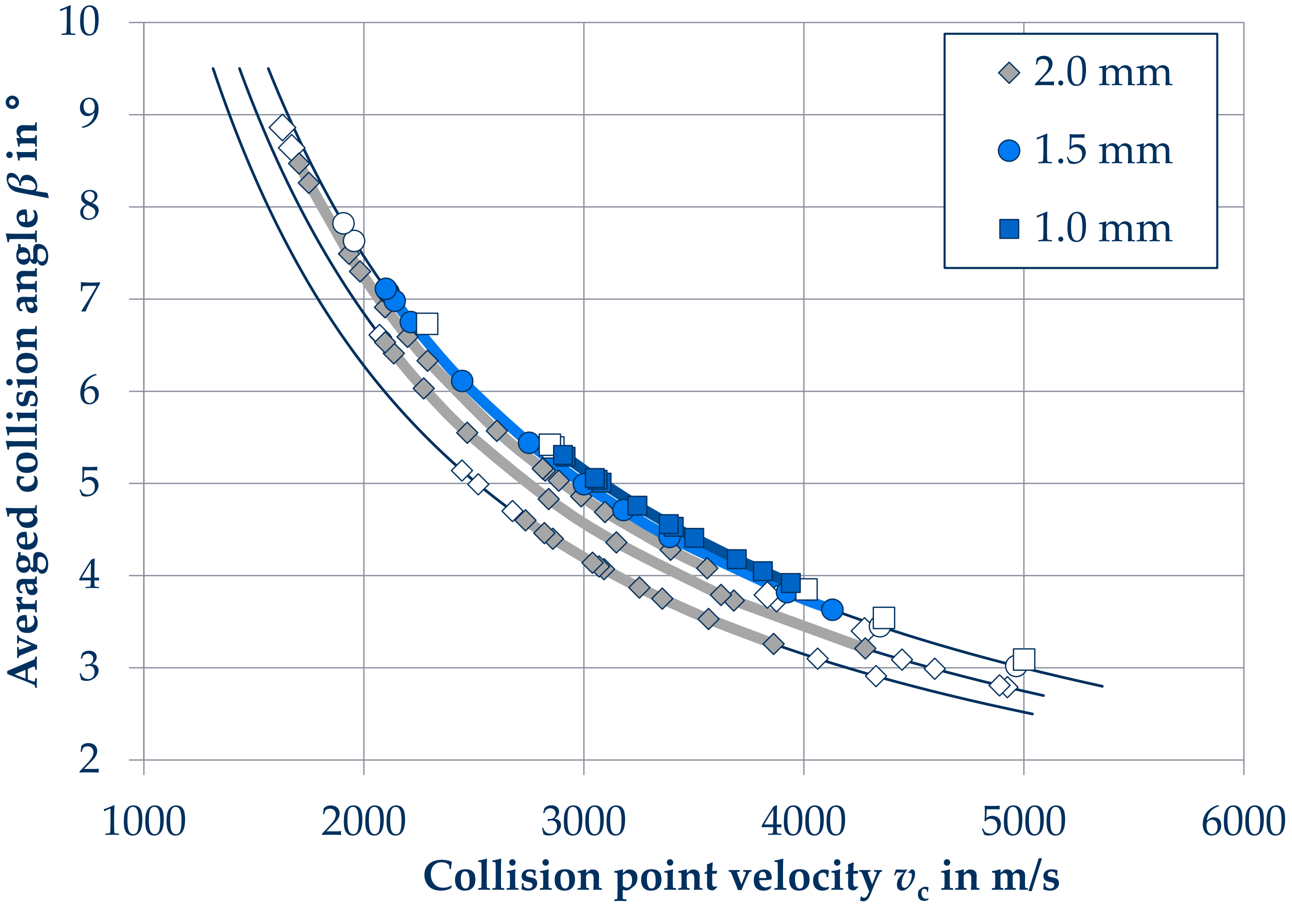
# 3. Influence of the flyer mass

## Findings (#1)




The increase of the kinetic impact energy (either by the flyer mass or the impact velocity) expands the upper boundary of the collision angle.

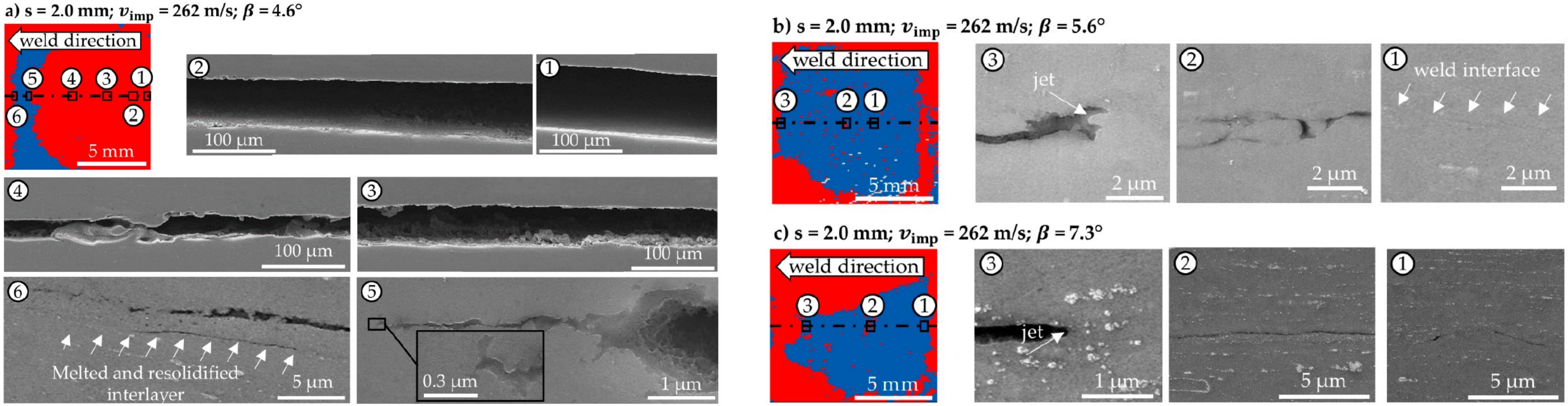
# 3. Influence of the flyer mass
## Findings (#1)




Increasing the flyer thickness *s* expands the upper boundary of the collision angle.

# 3. Influence of the flyer mass

## Findings (#1)

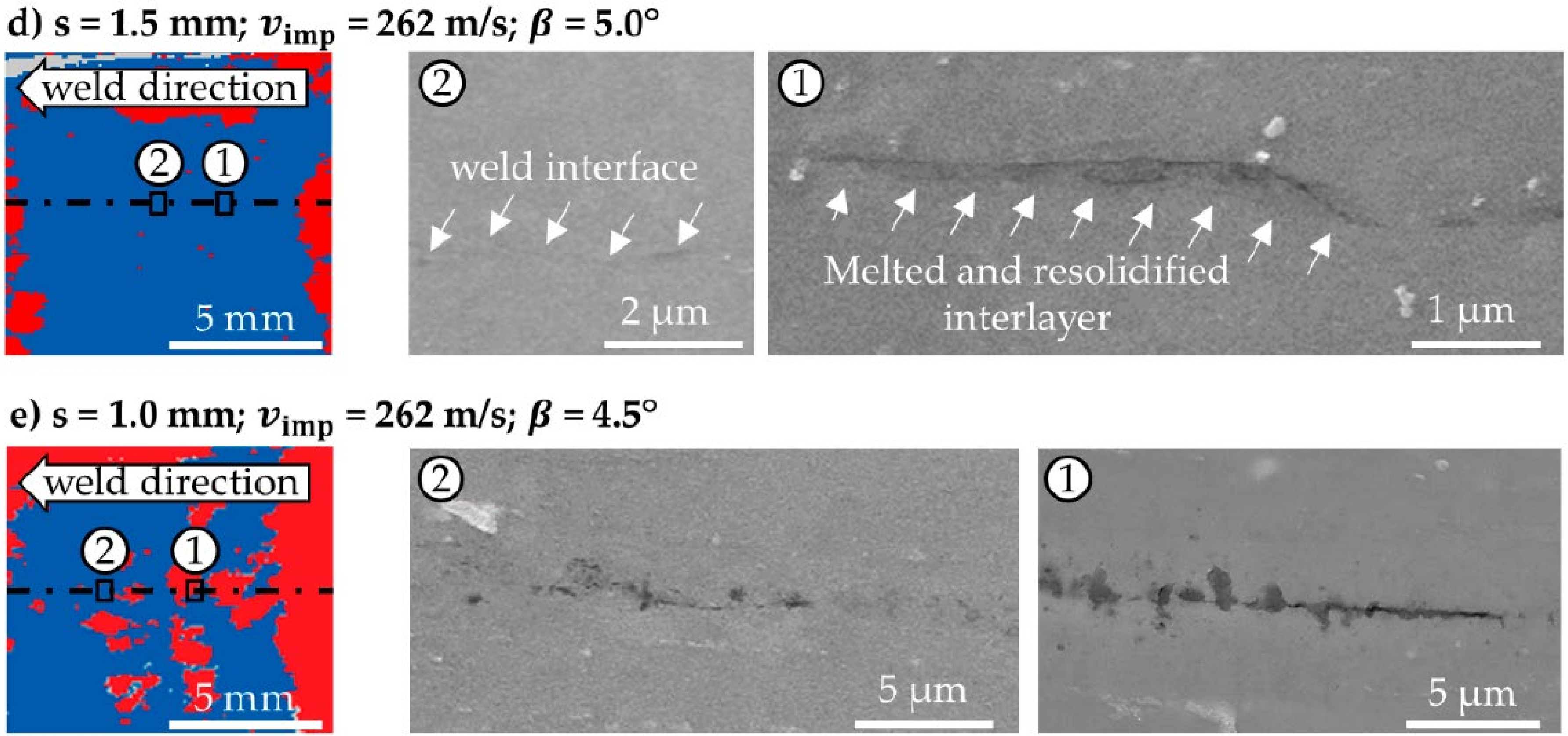



The collision angle determines the microstructure of the joining zone.

Small angles: thermal effects (melting, solidification)
Large angles: mechanical influences (plastic deformation, jet)

# 3. Influence of the flyer mass

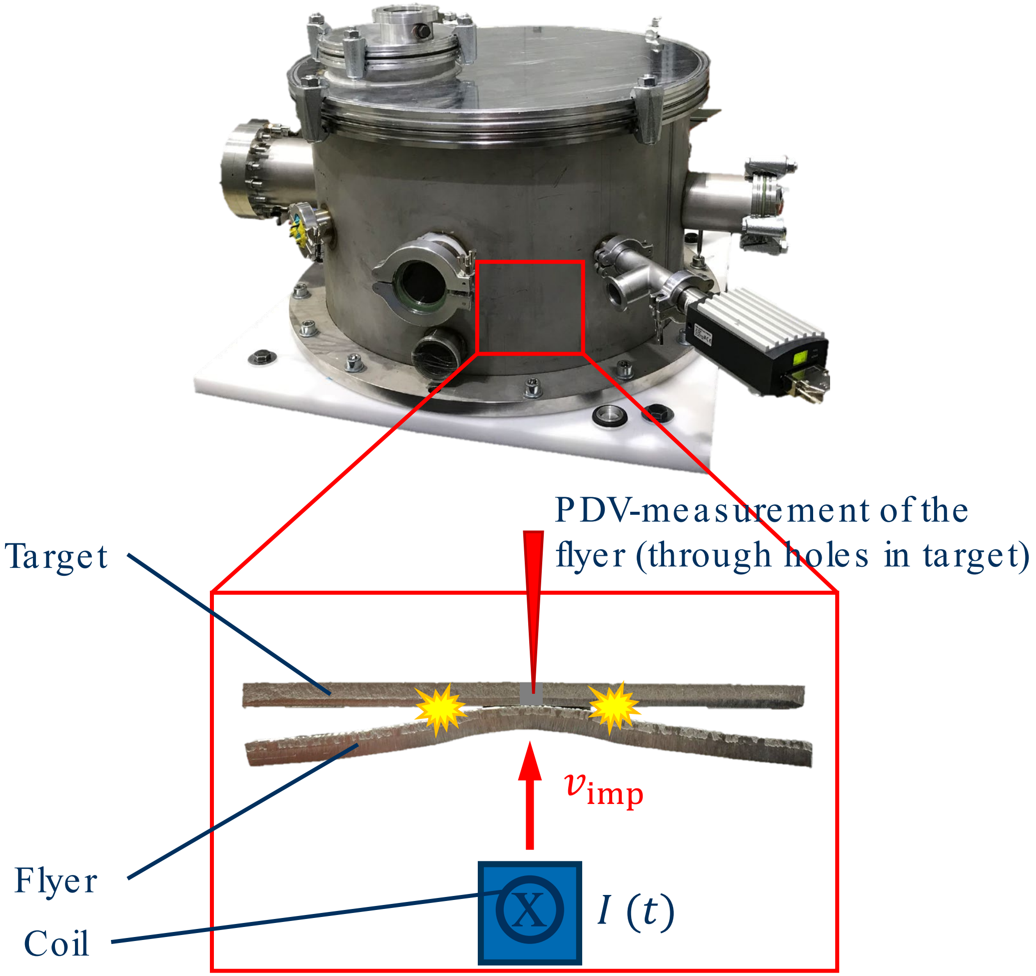
## Findings (#1)

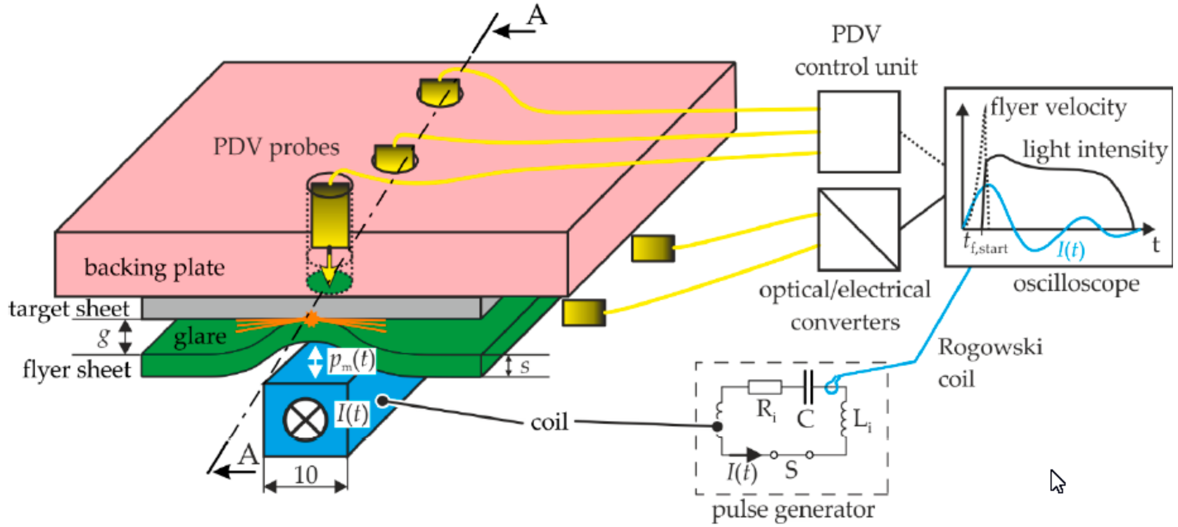


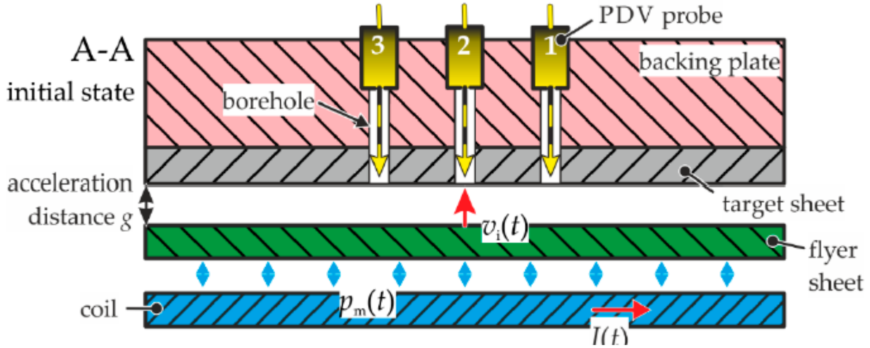

The reduction of the wall thickness *s* decreases the upper boundary of the collision angle. Thus, thermal effects dominate during the joining process.

# 3. Influence of the flyer mass

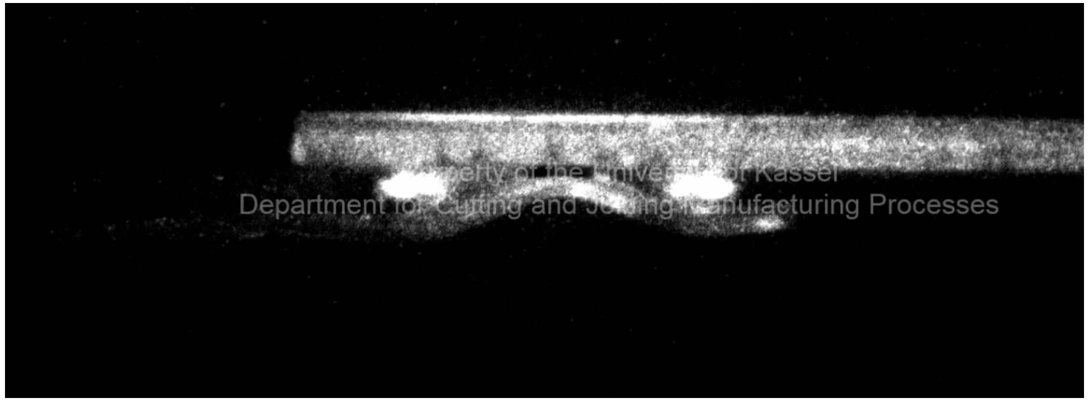
## Experimental Setups (#2 EMPT machine with vacuum chamber)



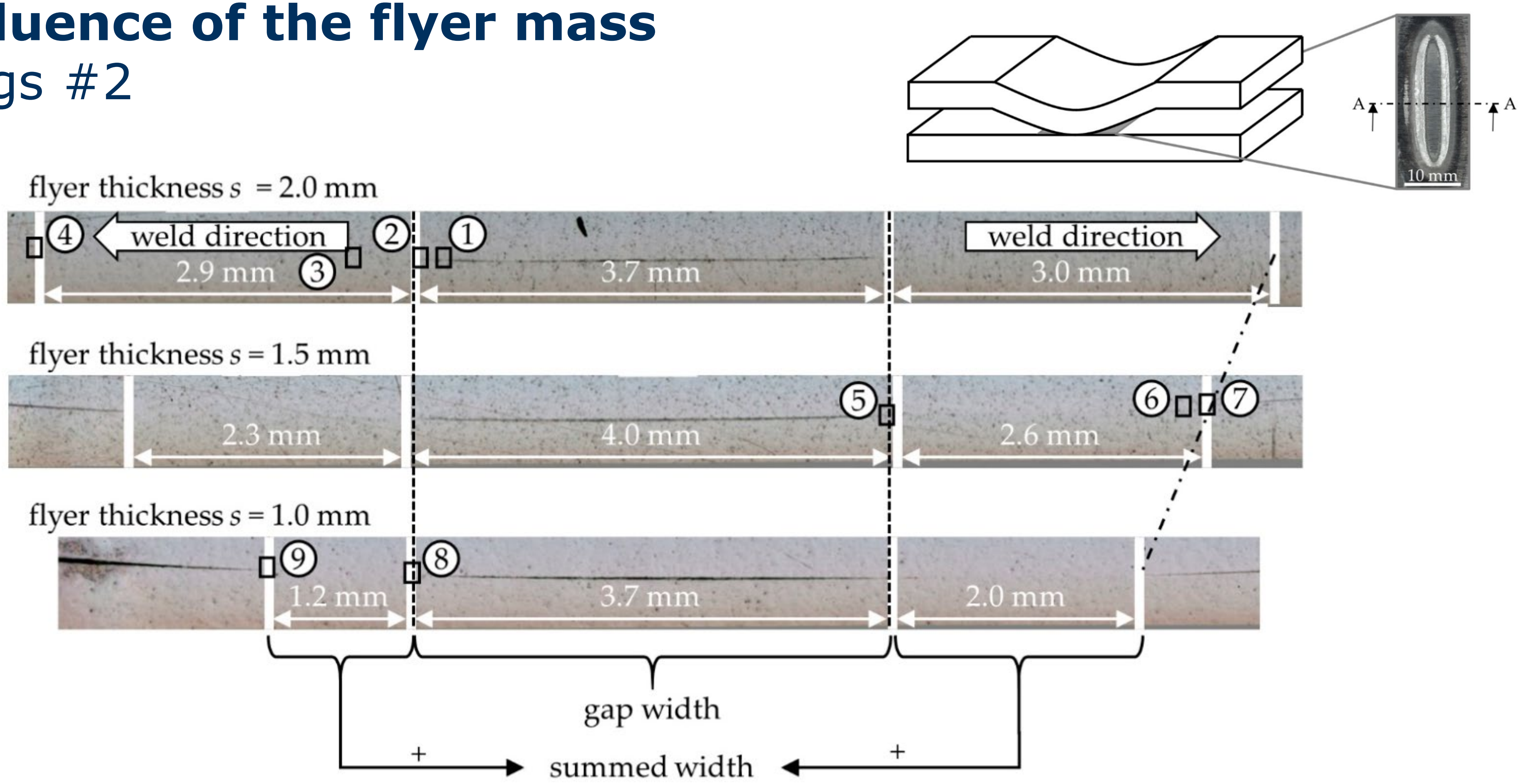
# 3. Influence of the flyer mass
## Findings #2





[E. Schumacher, A. Rebensdorf, S. Böhm, *Influence of the jet velocity on the weld quality of magnetic pulse welded dissimilar sheet joints of aluminum and steel*, in «Materialwissenschaft und Werkstofftechnik», 50, 2019, n. 8, pp. 965–972]

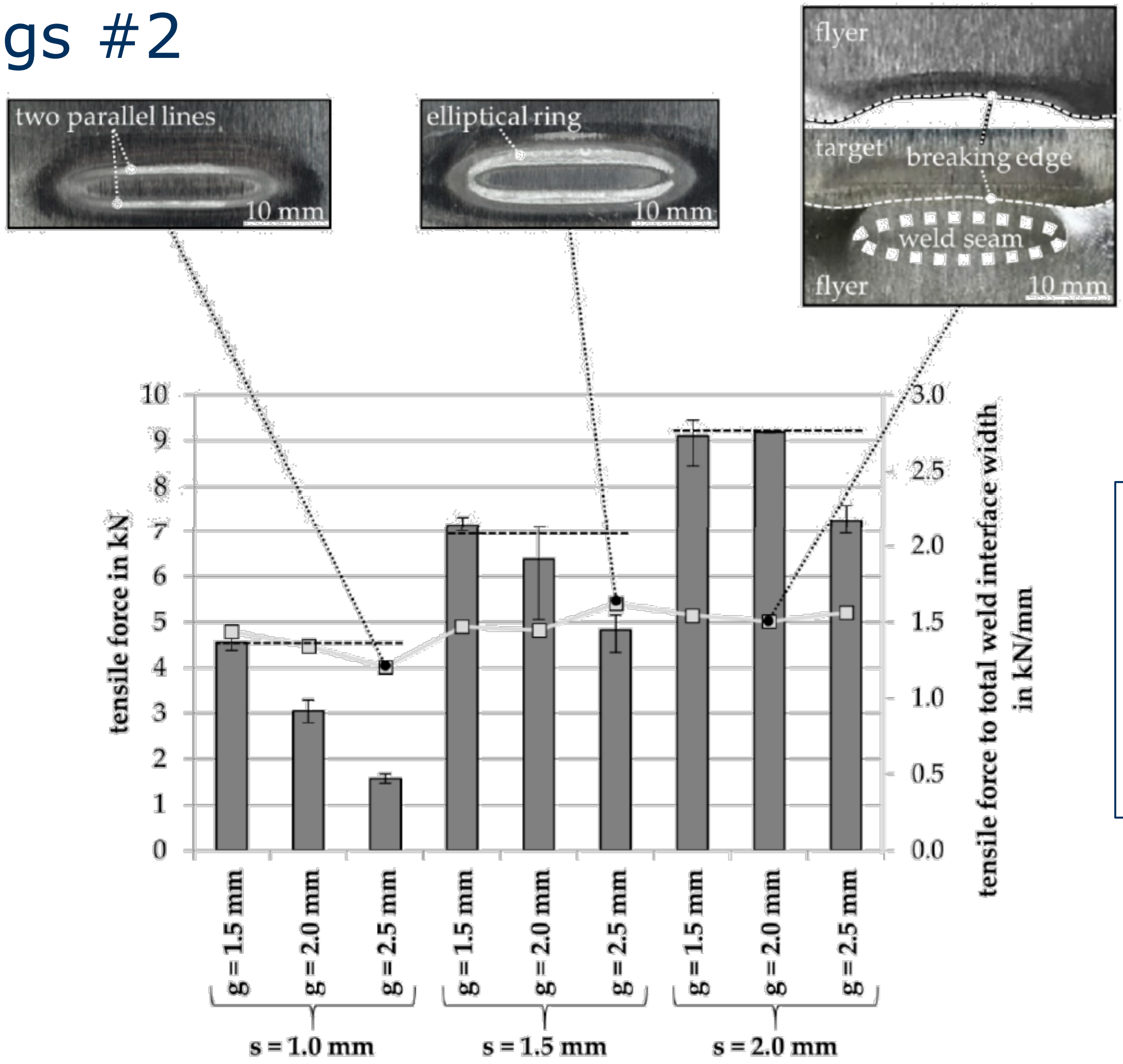
# 3. Influence of the flyer mass
## Findings #2




The increase of the wall thickness *s* does not effect the gap width, but increases the summed width of the weld seams.

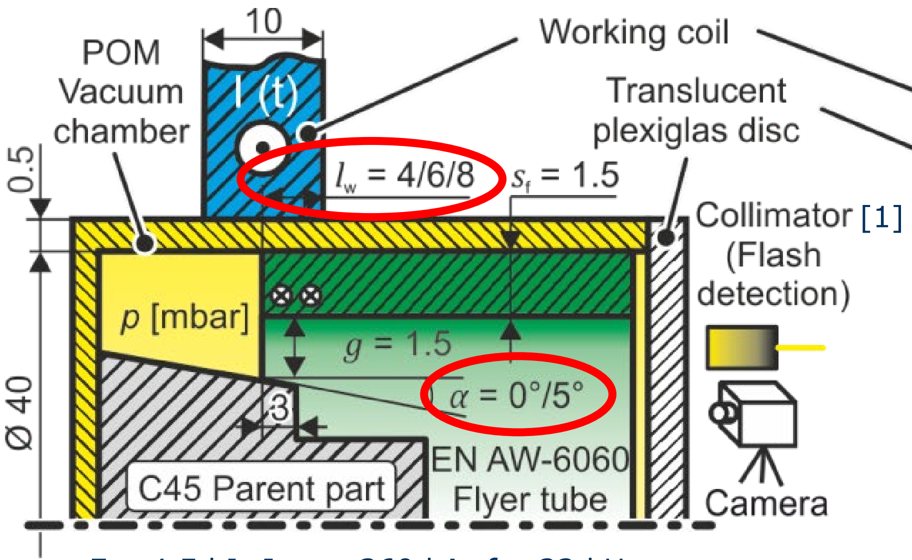
# 3. Influence of the flyer mass

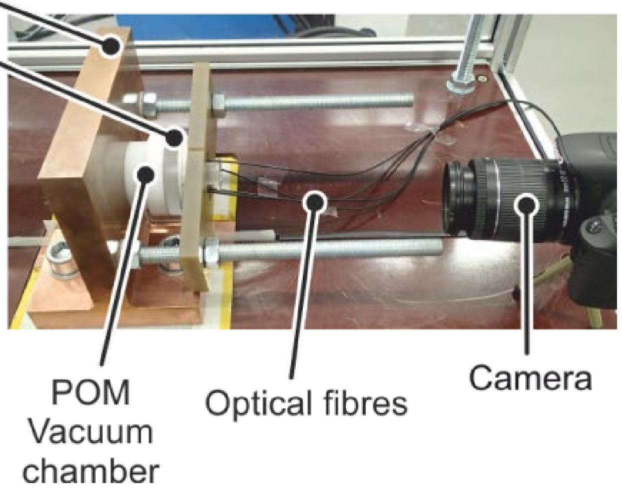
## Findings #2




Small flyer thicknesses *s* lead to lower strength of the weld interface, especially for larger collision angles.

# 4. Influence of the Temperature
## Experimental Setup #3



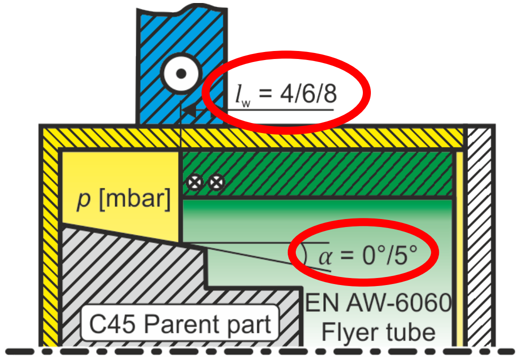

$E$ = 4.5 kJ, $I_{max}$ = 360 kA, $f$ = 22 kHz

Variation of working lenth $l_w$ and parent angle $\alpha$ →
Targeted manipulation of the collision angle $\beta$

Bellmann, Joerg (2018): Patent WO 2018/050569 A1 Method and Device for Monitoring the Process for a Welding Seam Formed by Means of Collision Welding

# 4. Influence of the Temperature

## Findings #3




| Case number | #1 | #2 | #3 | #4 | #5 |
|---|---|---|---|---|---|
| Working length $l_w$ [mm] | 6 | 4 | 6 | 8 | 6 |
| Parent chamfer $\alpha$ | 0° | 0° | 0° | 0° | 5° |
| Surrounding pressure $p$ [mbar] | 1000 | 0.1 | 0.1 | 0.1 | 0.1 |
| Initial collision angle $\beta_{Sim}$ | 6.4° | 9.5° | 6.4° | 3.4° | 9.9° |
| Process glare with average R/G/B value (5x5 pixels) at the indicated position<br>Black: 0/0/0<br>White: 255/255/255 |  254/254/253 |  46/16/7 |  201/133/117 |  201/249/253 |  98/42/26 |
| Circumferential weld | No | No | Yes | Yes | No |

Collision angle influences the process glare and welding result

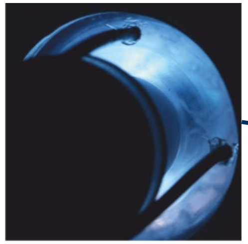
# 4. Influence of the Temperature

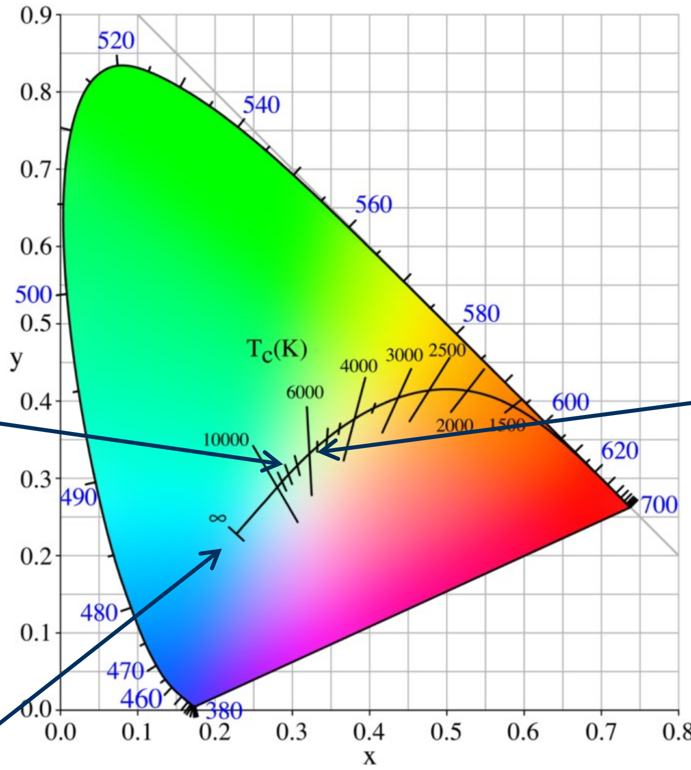
## Findings #3

CIE 1931 color space chromaticity diagram

$l_w$ = 8 mm

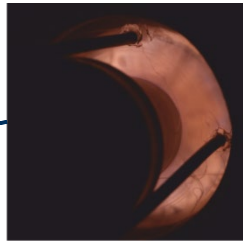
$\beta_{Sim}$ = 3.4°
$\beta_{Exp}$ = 5.0°
T ≈ 8000 K

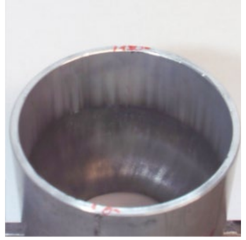





$l_w$ = 6 mm

$\beta_{Sim}$ = 6.4°
$\beta_{Exp}$ = 7.6°
T ≈ 5500 K



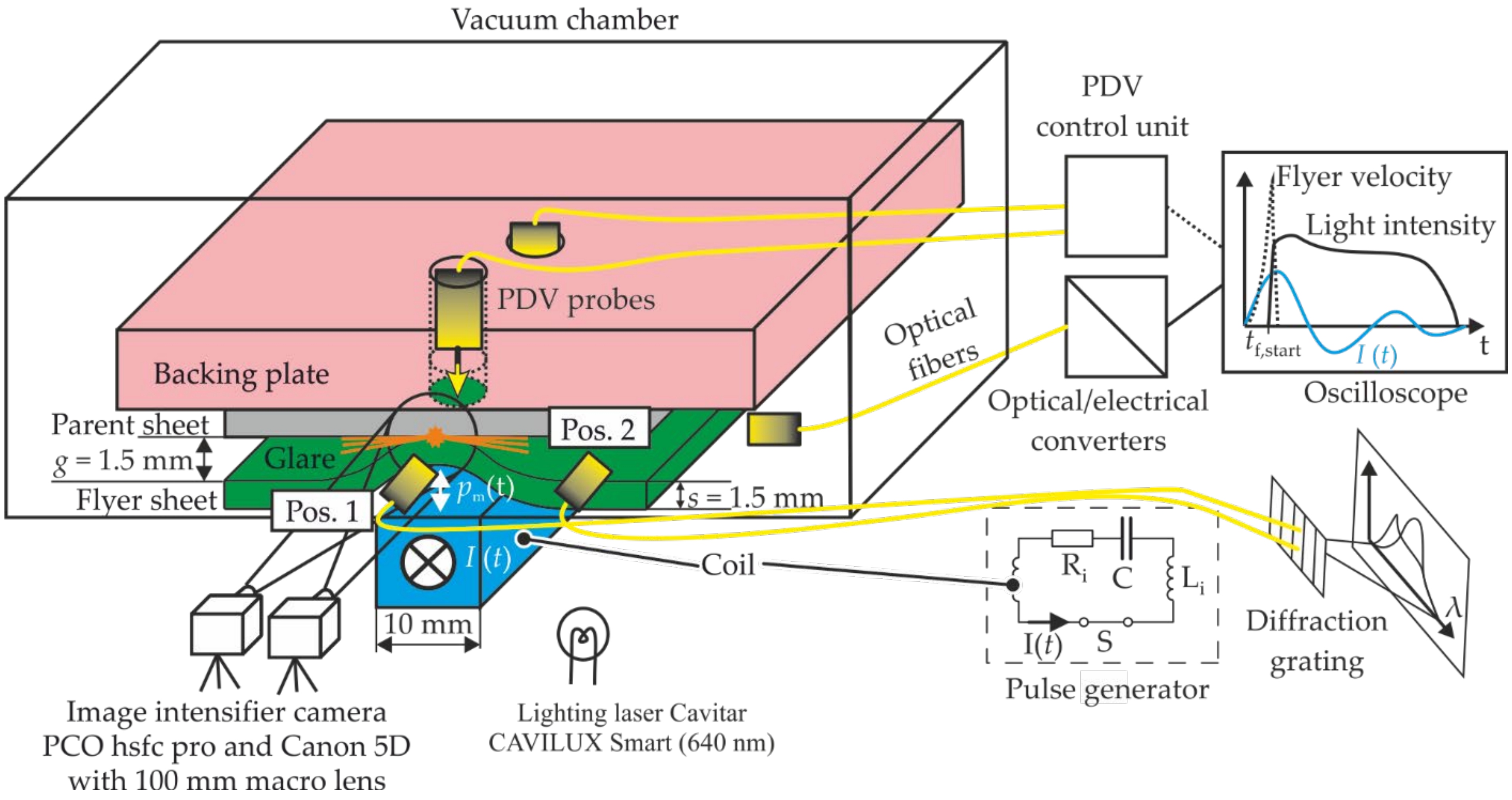


Chromaticity of black-body light sources of various temperatures (Planckian locus)

https://en.wikipedia.org/wiki/Color_temperature (06/20/2019)

Small collision angle $\beta$ leads to higher temperature in the joining gap

# 4. Influence of the Temperature
## Experimental Setup #4

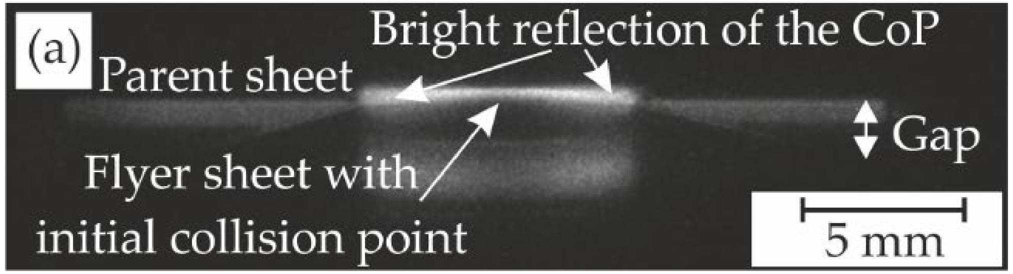


# 4. Influence of the Temperature

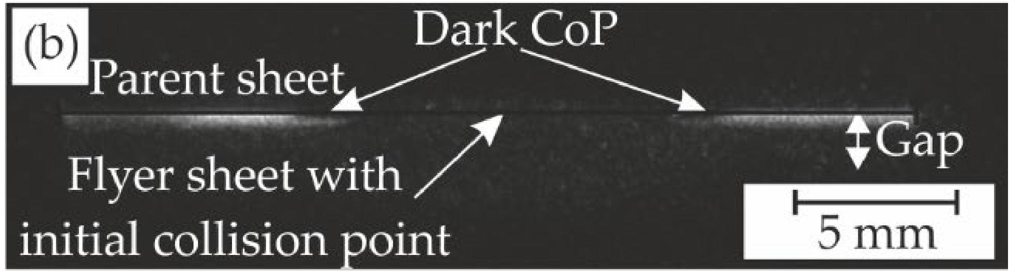
## Findings #4

$V_{imp}$ ~243 m/s

p = 100,000 Pa




p = 100 Pa




p = 100,000 Pa

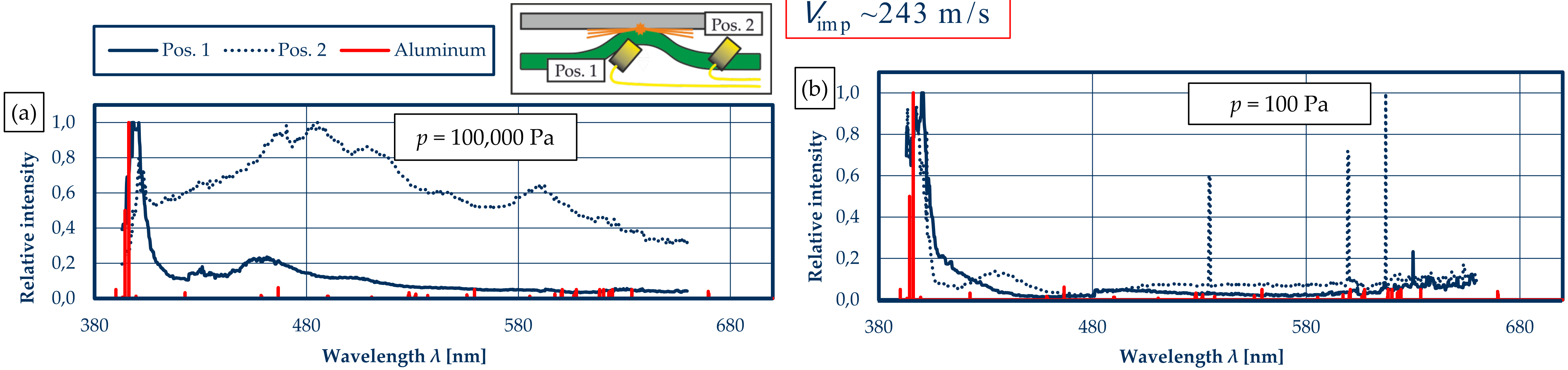

p = 100 Pa


Surrounding pressure *p* influences the process glare

# 4. Influence of the Temperature

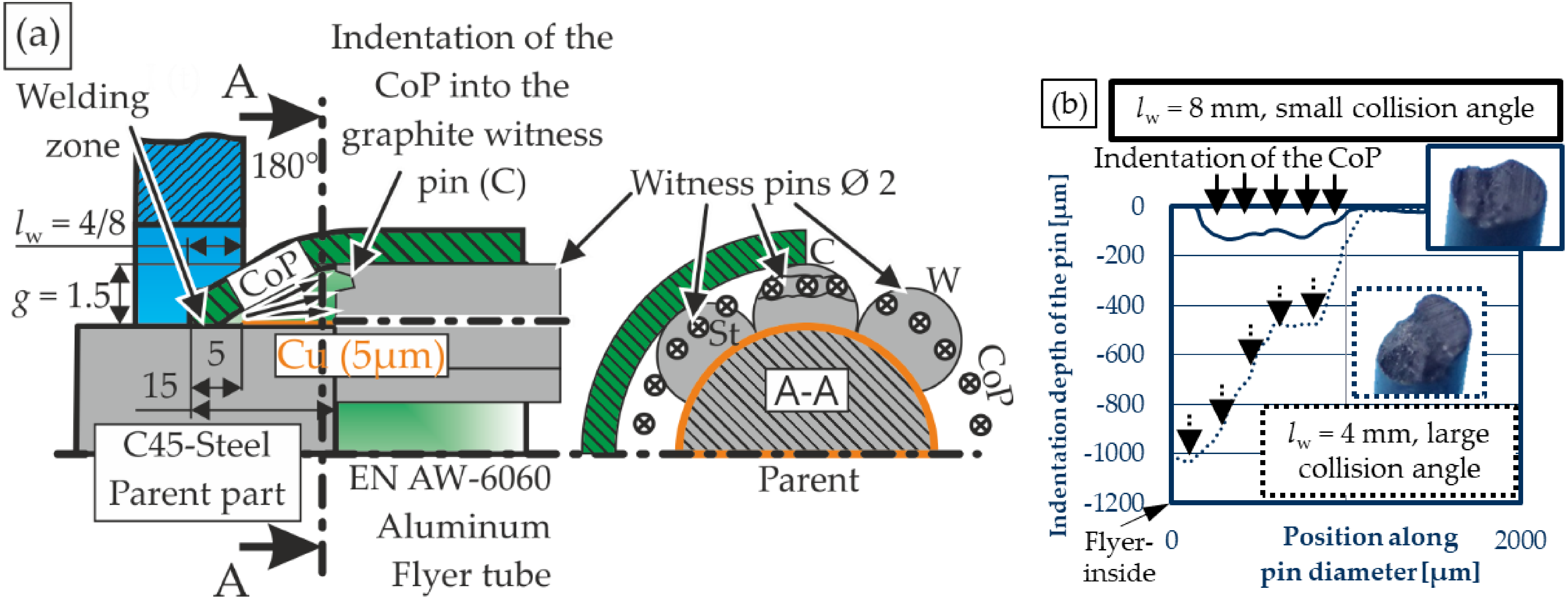
## Findings #4

$V_{imp}$ ~243 m/s

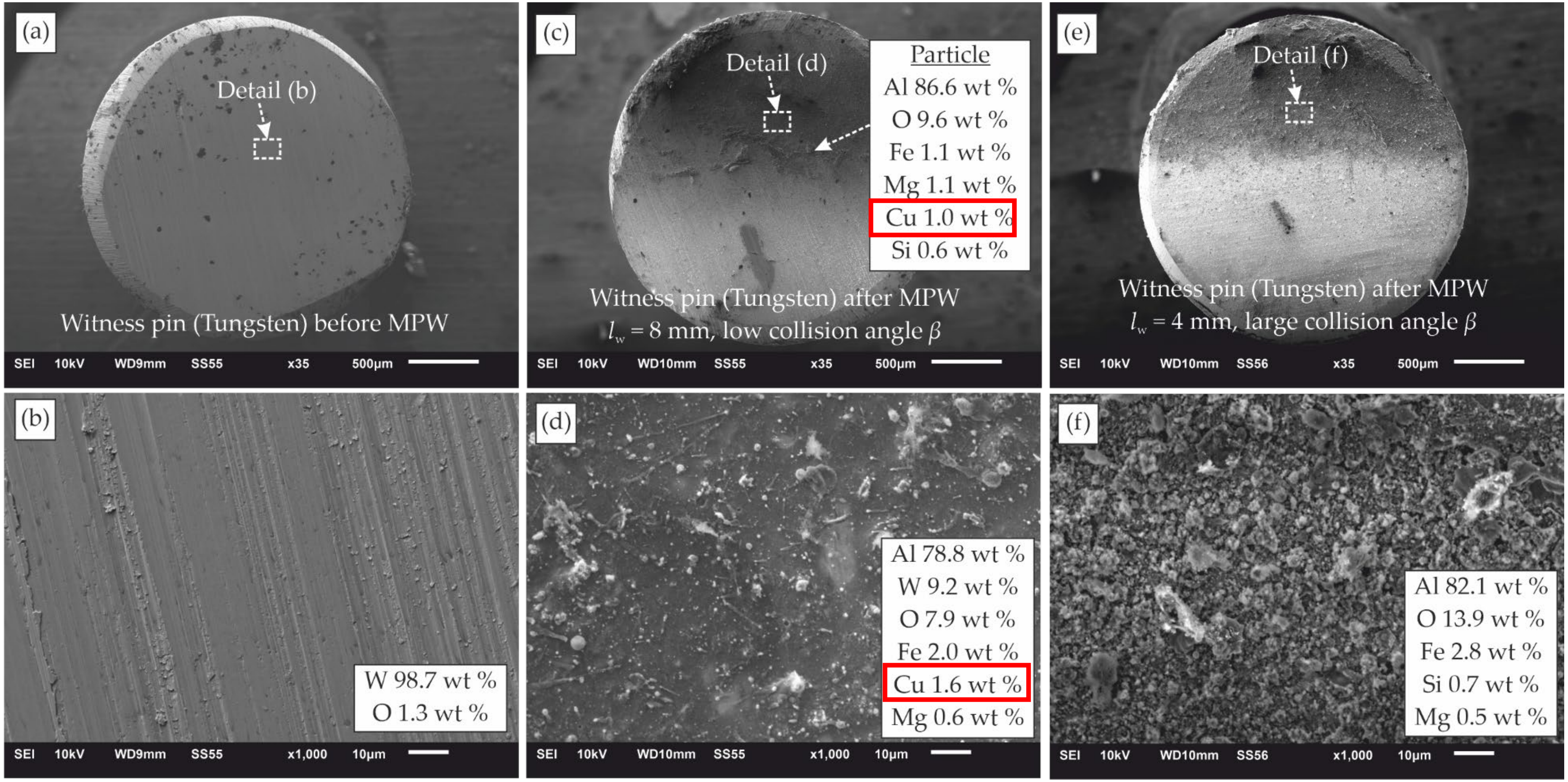



The relative spectral intensities were measured and allow for a temperature estimation in the joining gap: 5600 K.

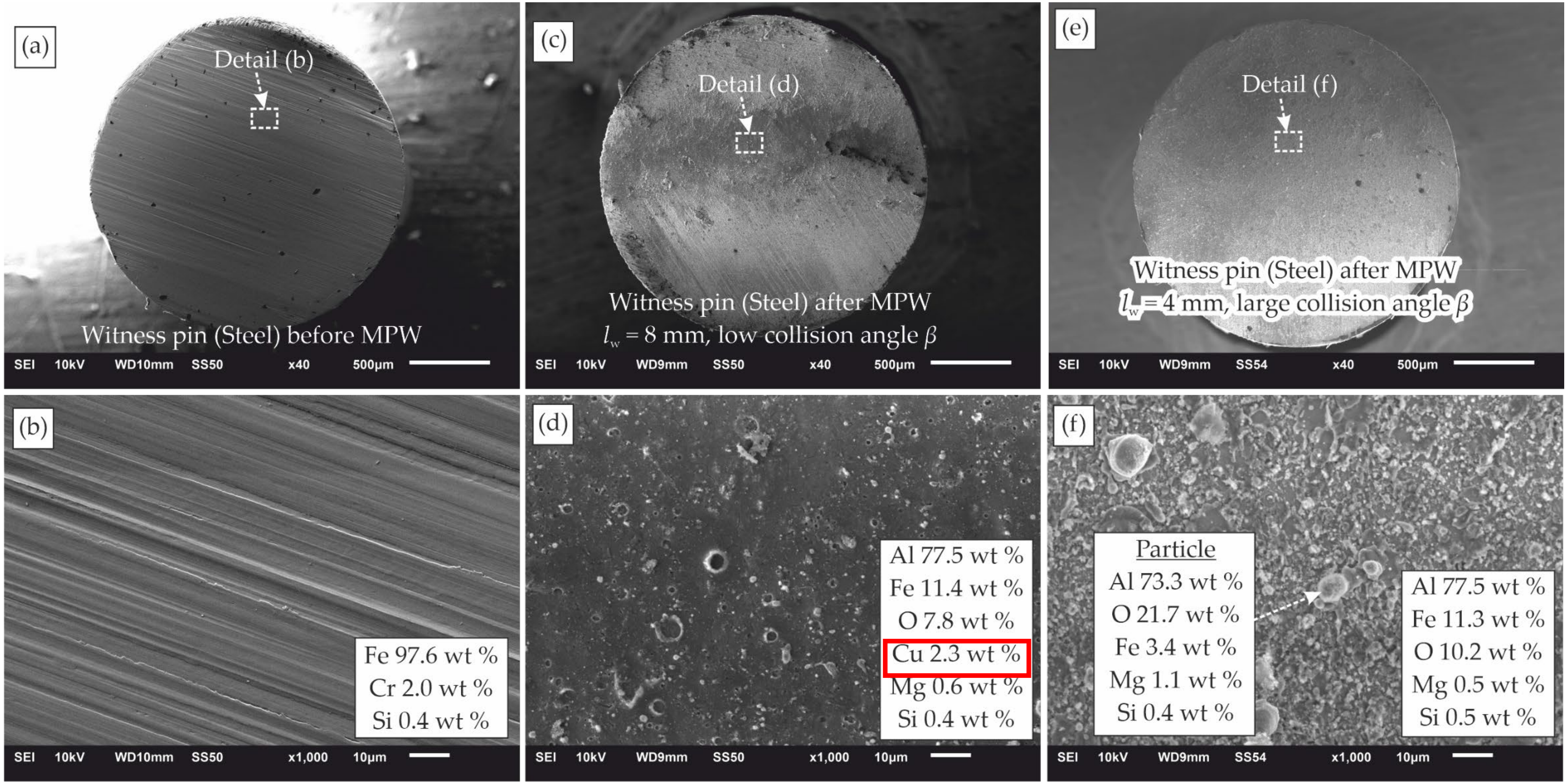
# 4. Influence of the Temperature
## Experimental Setup and Findings #5



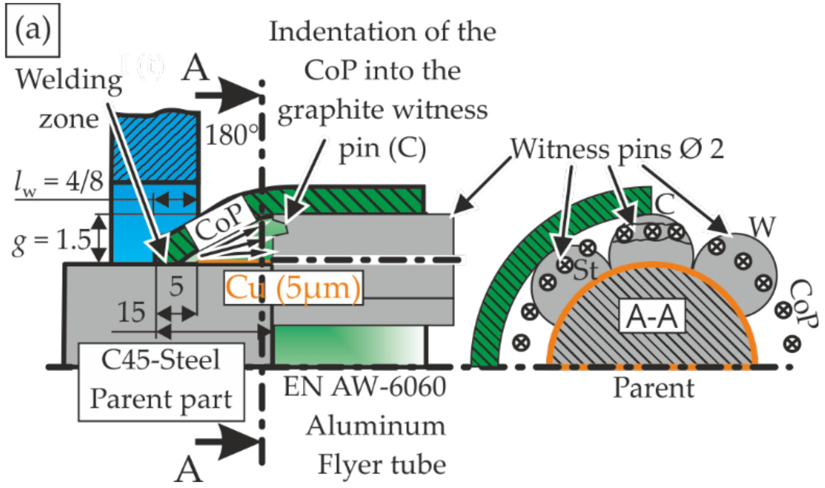
# 4. Influence of the Temperature
## Findings #5

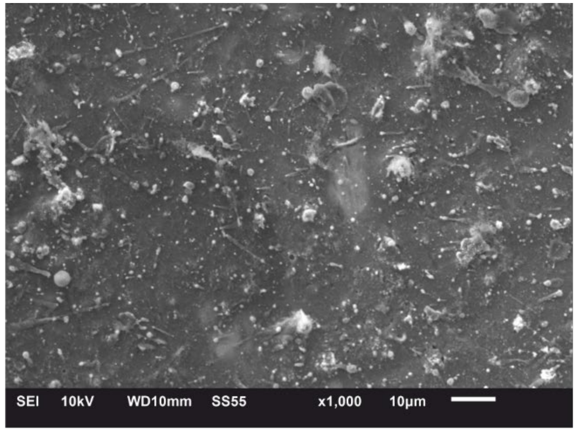


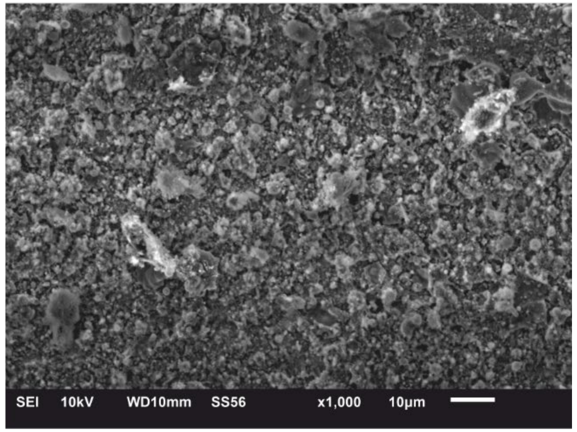
# 4. Influence of the Temperature
## Findings #5



# 4. Influence of the Temperature
## Findings #5



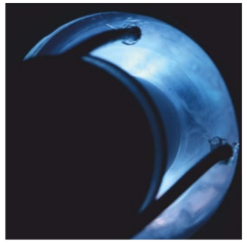



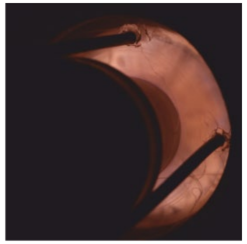

| Collision angle $\beta$ | Low | Large |
|---|---|---|
| Temperature in the joining gap | High (~8000 K) | „low“ (< 5000 K) |
| Vaporized witness pin surface | Contains copper tracer | Contains no copper |
| Structure of the vaporized witness pin surface | Finely dispersed | Ragged surface, small aluminum particles |
| Welding result | Welded | Not welded |

# 4. Influence of the Temperature
## Consolidated Findings #5

- The effect of the collision angle can be monitored optically or by witness pins.
- The collision angle determines the temperature in the joining gap ($v_{imp}$ = const.).
  - Small collision angles
    - Lead to higher temperatures in the joining gap due to intensive compression of the Cloud of Particles (CoP)
    - Support the surface melting of the joining partners
    - Generate a fine dispersed metal vapor
    - Support the fusion welding mechanism



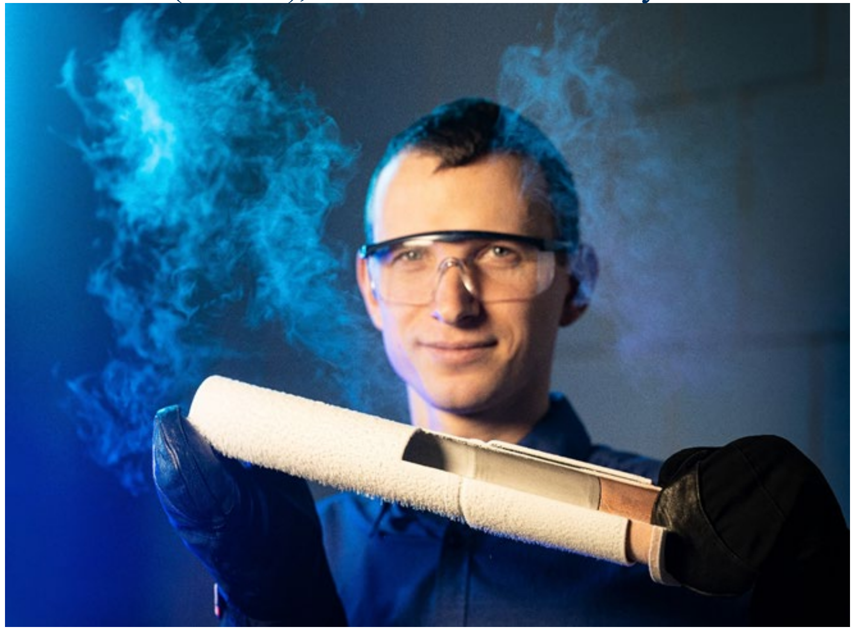
  - Large collision angles
    - Lead to lower temperatures
    - Generate a coarse metal vapor including particles with high kinetic energy
    - May not enable welding, if the the impact velocity is too low



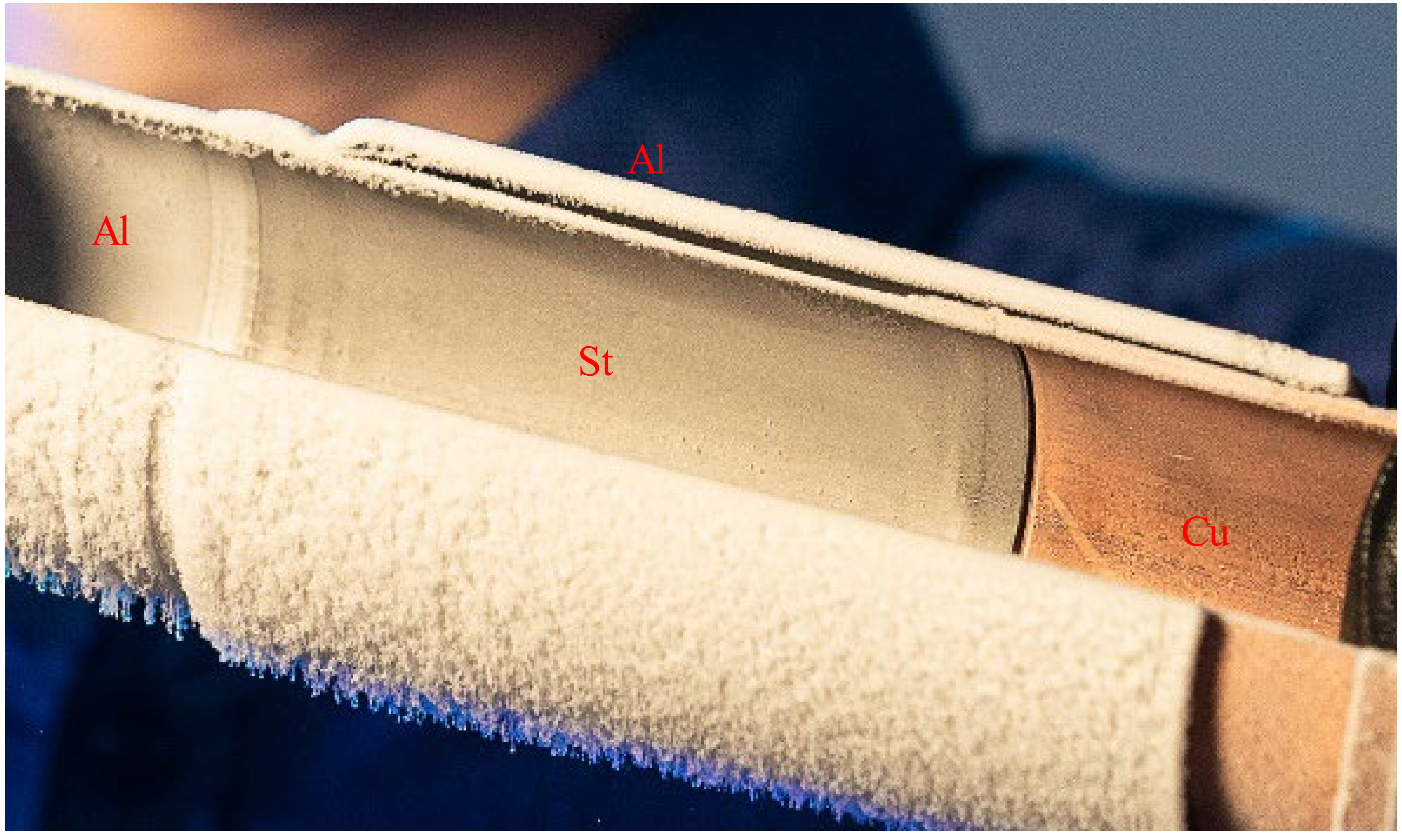
# 5. Cool Application!

## Application temperature is 1 K.

At the research Neutron Source Heinz Maier-Leibnitz (FRM II), Technical University of Munich



[Fraunhofer IWS, 2020]



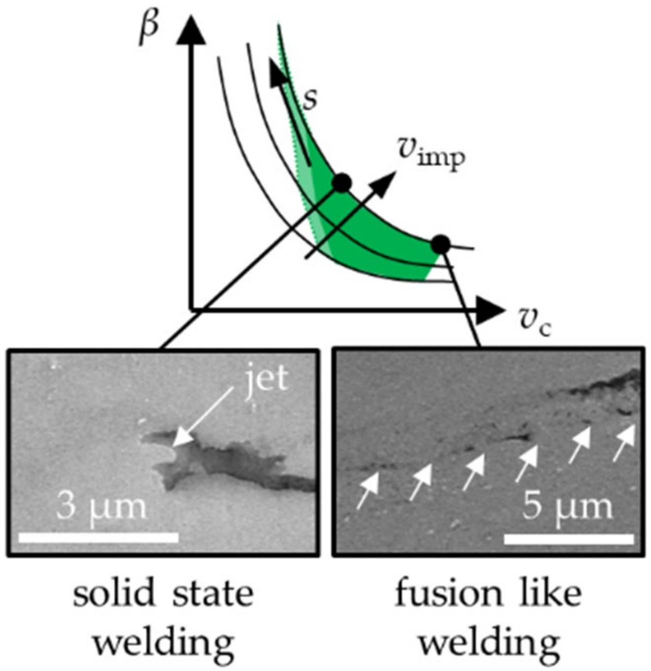

- Kryogenic cup (Ø 50 mm) made of aluminum, stainless steel and copper → 3 magnetic pulse welded zones
- 15 times: shock cooling and heating from room temperature to 77 K and vice versa
- Proof of leak-tightness with an inner pressure of $10^{-2}$ mbar at both temperature levels
- Video: https://www.youtube.com/watch?v=PTZkB4KuuKc

# 6. Conclusion

The welding result of impact welding processes is determined by:

1. **The kinetic flyer energy**
   - velocity (traditional welding windows)
   - Mass → welding mechanism (press welding / fusion welding)

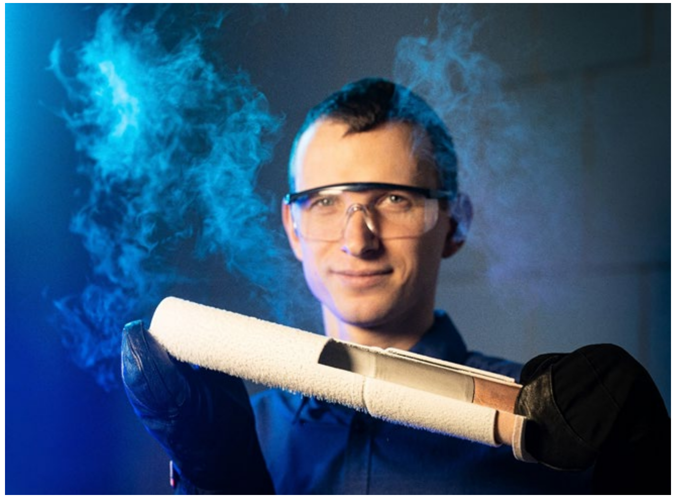
2. **The temperature in the joining gap**
   - Can be controlled by the collision angle
   - Determines the properties of the Cloud of Particles (CoP) and the Jet
   - Is responsible for the surface melting *before* contact
   - Supports the reduction of forces on the tool coils and joining partners



# Acknowledgement

Hot!

Cool!



Thanks:

- For your kind attention,
- For the financial support by the German Research Foundation (DFG) during SPP1640,
- For the friendly collaboration within the High-Speed Joining group!