U-Mo bare foil rolling progress for FRM II conversion

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FRM II conversion purposes

Current situation

Figure 1: FRM II research reactor (Garching, Germany)

FRM II conversion purposes

Current situation

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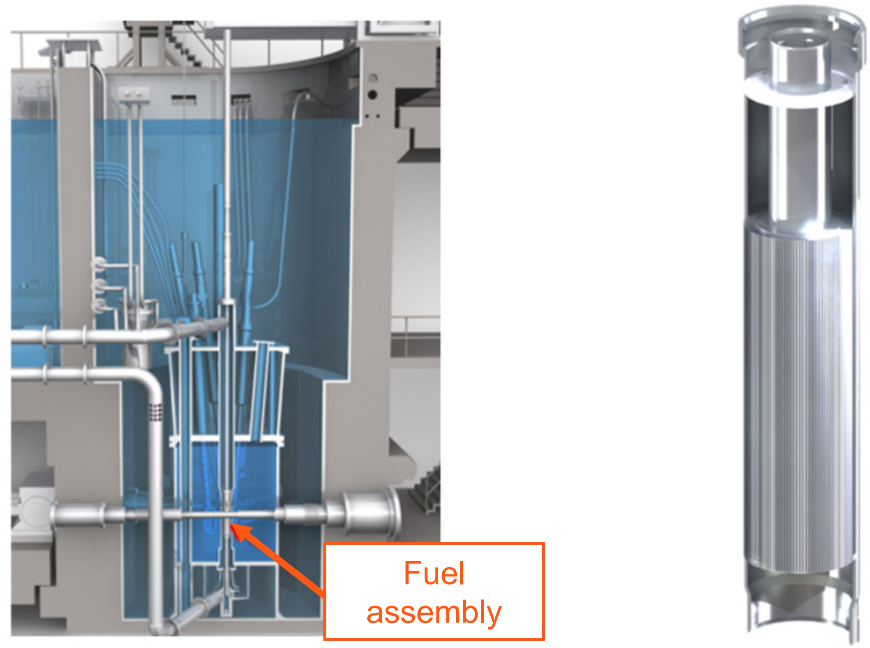

Figure 2: FRM II pool with fuel assembly scheme

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FRM II conversion purposes

Fuel conversion

Figure 3: Transverse cut of actual FRM II fuel

FRM II conversion purposes

Fuel conversion

Figure 3: Transverse cut of actual FRM II fuel

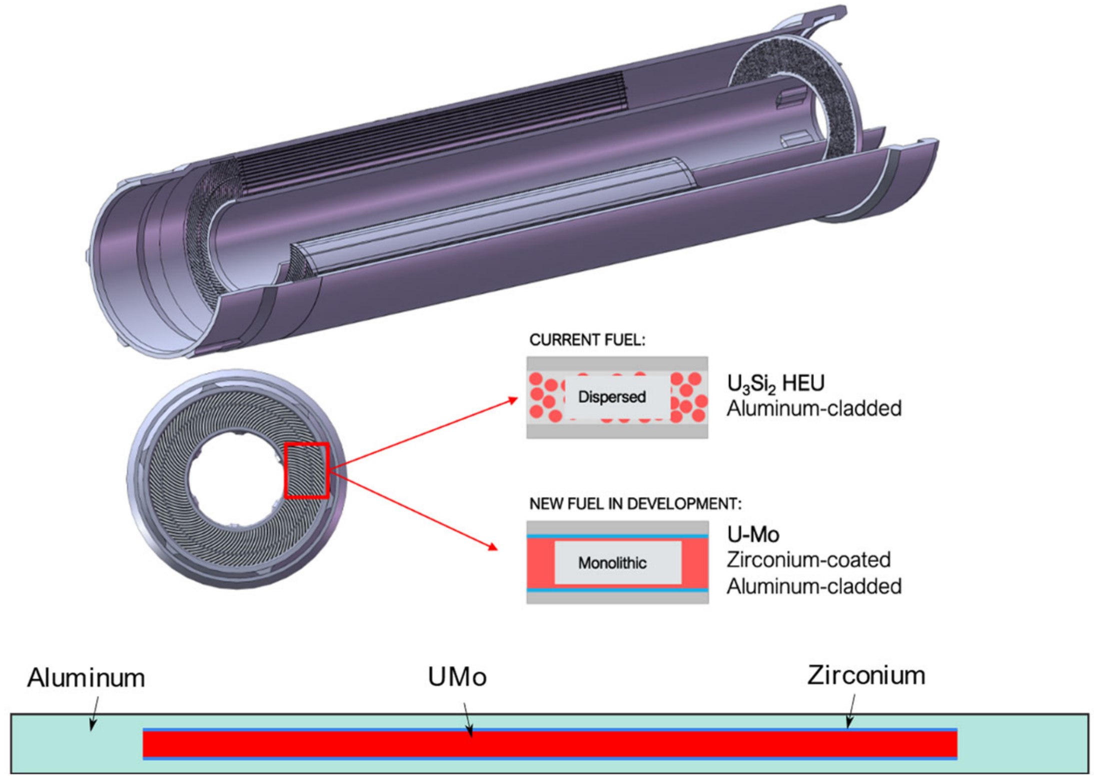


Figure 4: New FRM II fuel composition

FRM II conversion purposes

New fuel plate manufacturing process in Framatome

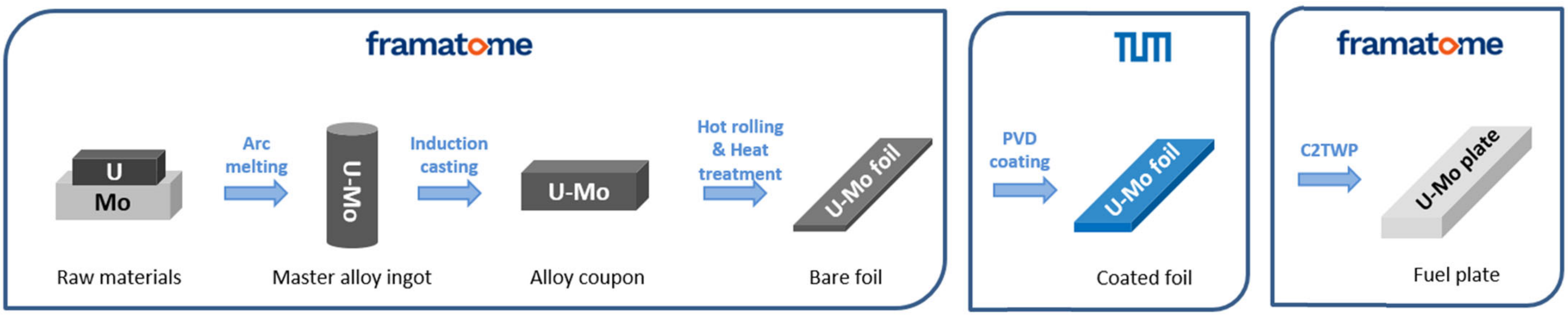


Figure 5: Manufacturing process flow for the new FRM II fuel

FRM II conversion purposes

Progress & schedule of R&D fuel development

Development of U-Mo alloy (**2020 - 2021**)

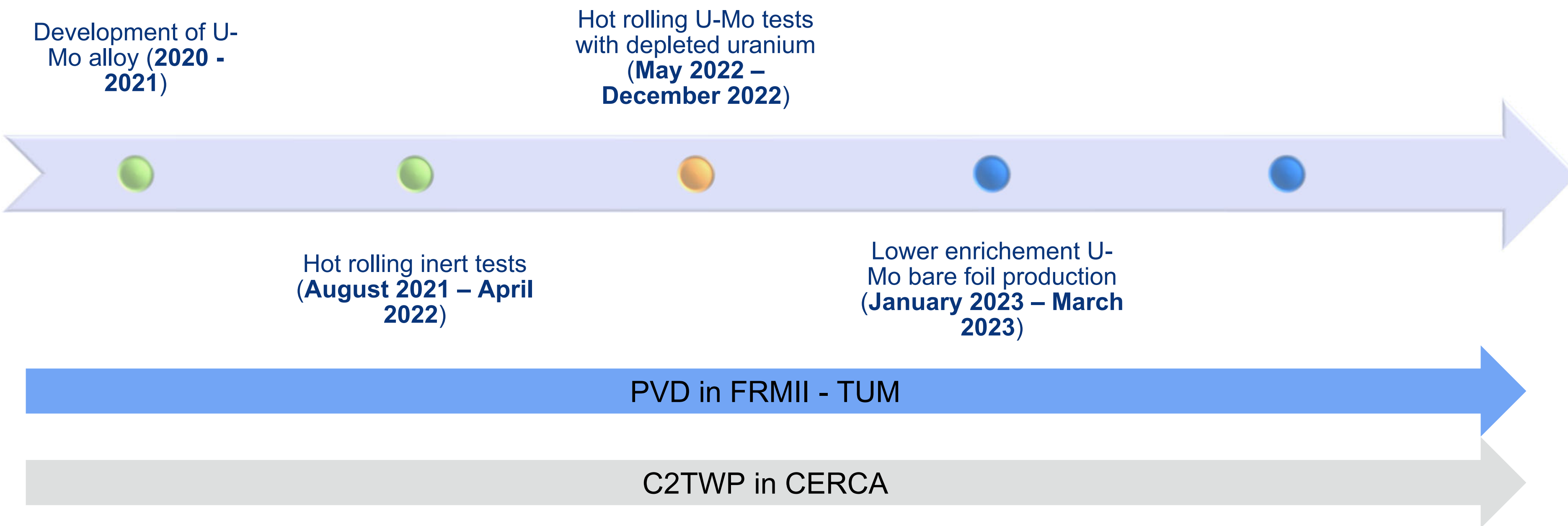
Hot rolling U-Mo tests with depleted uranium (**May 2022 – December 2022**)

Hot rolling inert tests (**August 2021 – April 2022**)

Lower enrichement U-Mo bare foil production (**January 2023 – March 2023**)

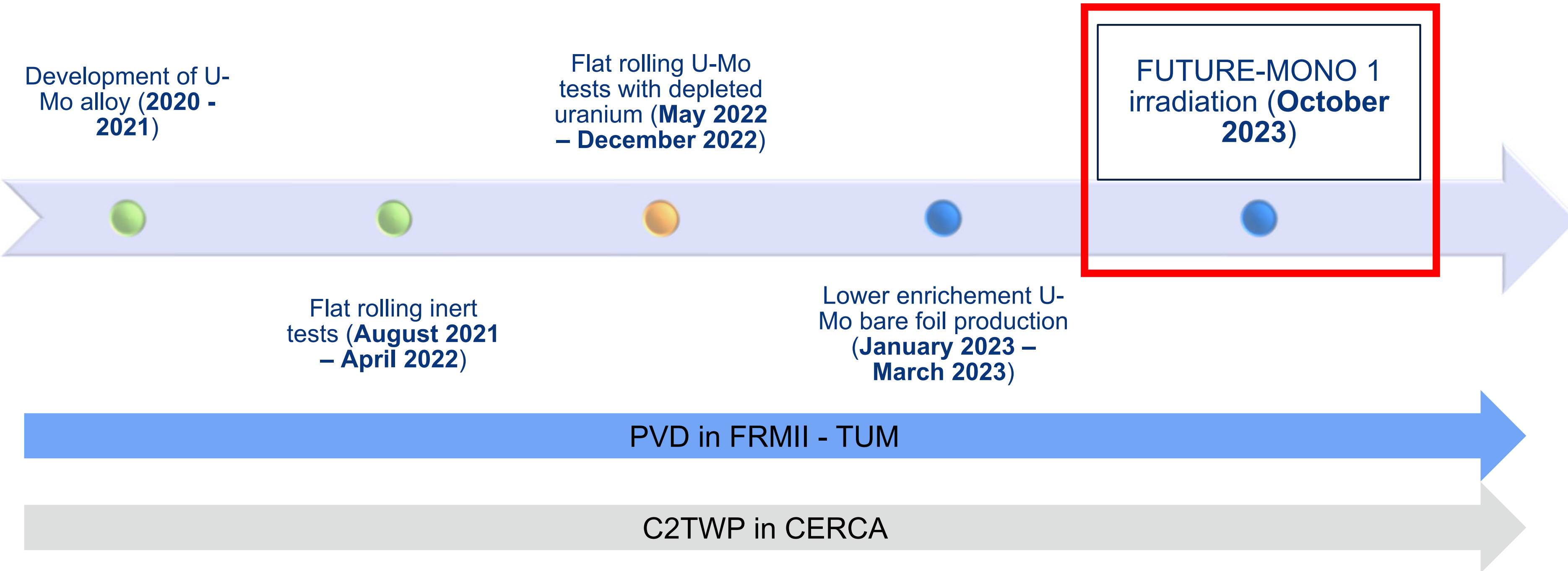
FRM II conversion purposes

Progress & schedule of R&D fuel development



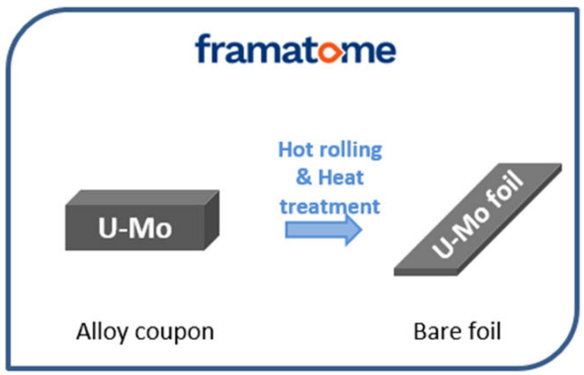
FRM II conversion purposes

Focus on for FUTURE-MONO 1 irradiation



FRM II conversion purposes

New fuel plate manufacturing process in Framatome



Focus on :

- **hot flat rolling**
- **U-Mo bare foil removing**

U-Mo flat rolling process

Equipment available for U-Mo rolling

- **Hot rolling mill characteristics**:
  - Rolling speed and roll gap controllable
  - Max. & min thickness: 20 to 0.1 mm
  - 2-Hi & 4-Hi according foil thickness

Figure 6: Hot rolling mill in CERCA lab

U-Mo flat rolling process

Equipment available for U-Mo rolling

- **Hot rolling mill characteristics**:
  - Rolling speed and roll gap controllable
  - Max. & min thickness: 20 to 0.1 mm
  - 2-Hi & 4-Hi according foil thickness
- **Cold rolling mill characteristics**:
  - Rolling speed and roll gap controllable
  - Max & min thickness: 1 to 0.1 mm
  - 4-Hi for foil finalization

Figure 6: Hot rolling mill in CERCA lab

Figure 7: Cold rolling mill into glovebox

U-Mo flat rolling process

Equipment available for U-Mo rolling

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  - Rolling speed and roll gap controllable
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Figure 6: Hot rolling mill in CERCA lab

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U-Mo flat rolling process

Hot flat rolling process manufacturing description

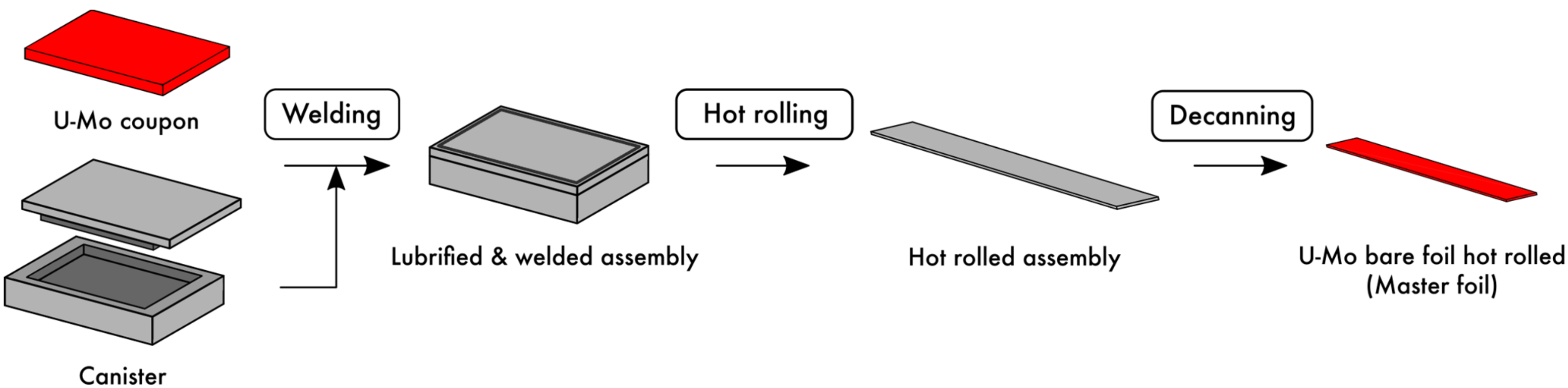
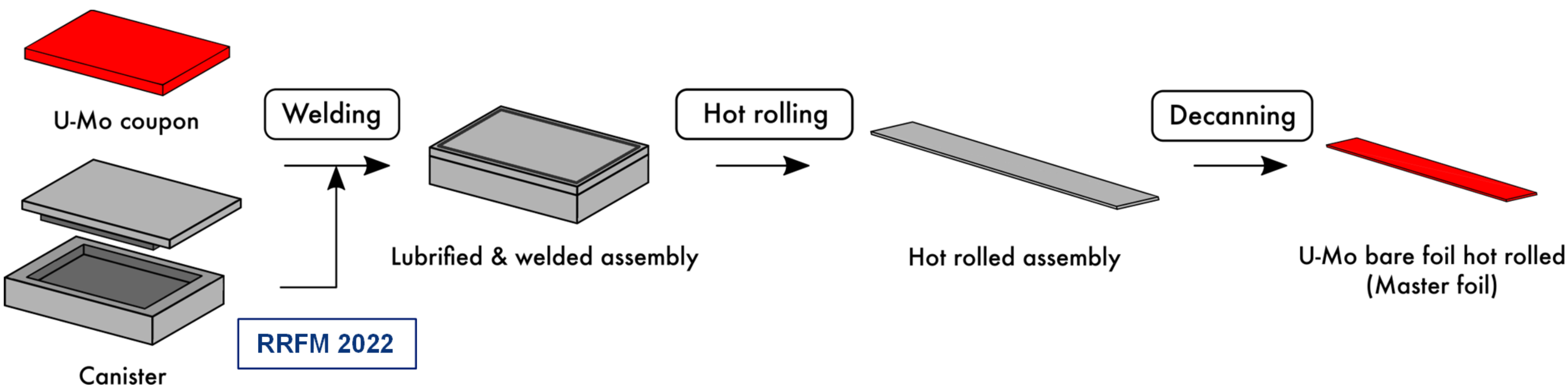


Figure 8: Flat rolling step for U-Mo bare foil manufacturing

U-Mo flat rolling process

Hot flat rolling process manufacturing description



DEVELOPMENT OF LASER PROCESSES ON U-10Mo MONOLITHIC FUEL FABRICATION PROCESS AT FRAMATOME (CERCA BUSINESS LINE)

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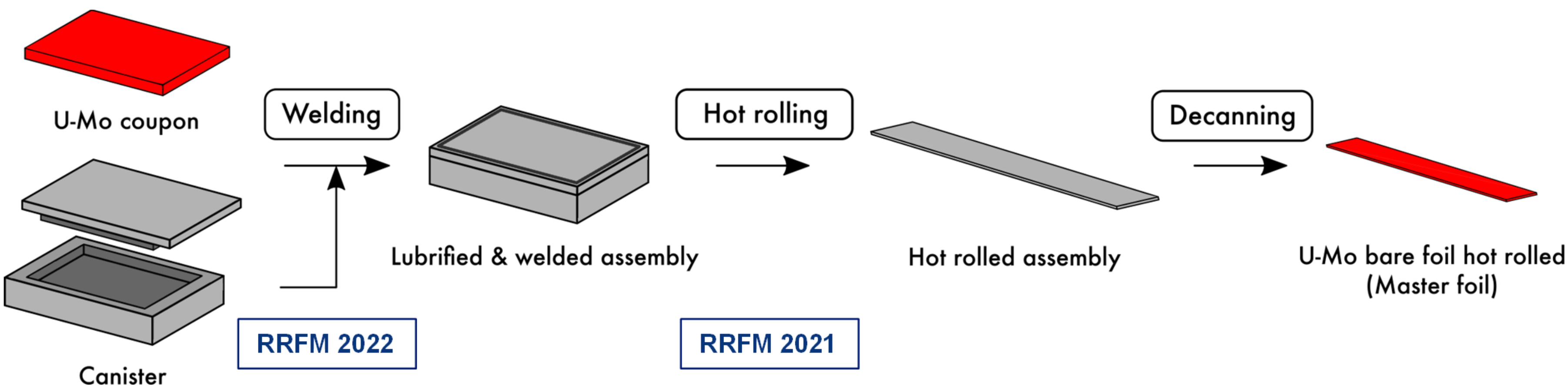
U-Mo flat rolling process

Hot flat rolling process manufacturing description



RRFM 2022

DEVELOPMENT OF LASER PROCESSES ON U-10Mo MONOLITHIC FUEL FABRICATION PROCESS AT FRAMATOME (CERCA BUSINESS LINE)

RRFM 2021

FIRST RESULTS OF THE EUROPEAN MANUFACTURING PROCESS FOR BARE U-MO

U-Mo flat rolling process

U-Mo bare foil hot rolled laser removed inside glovebox

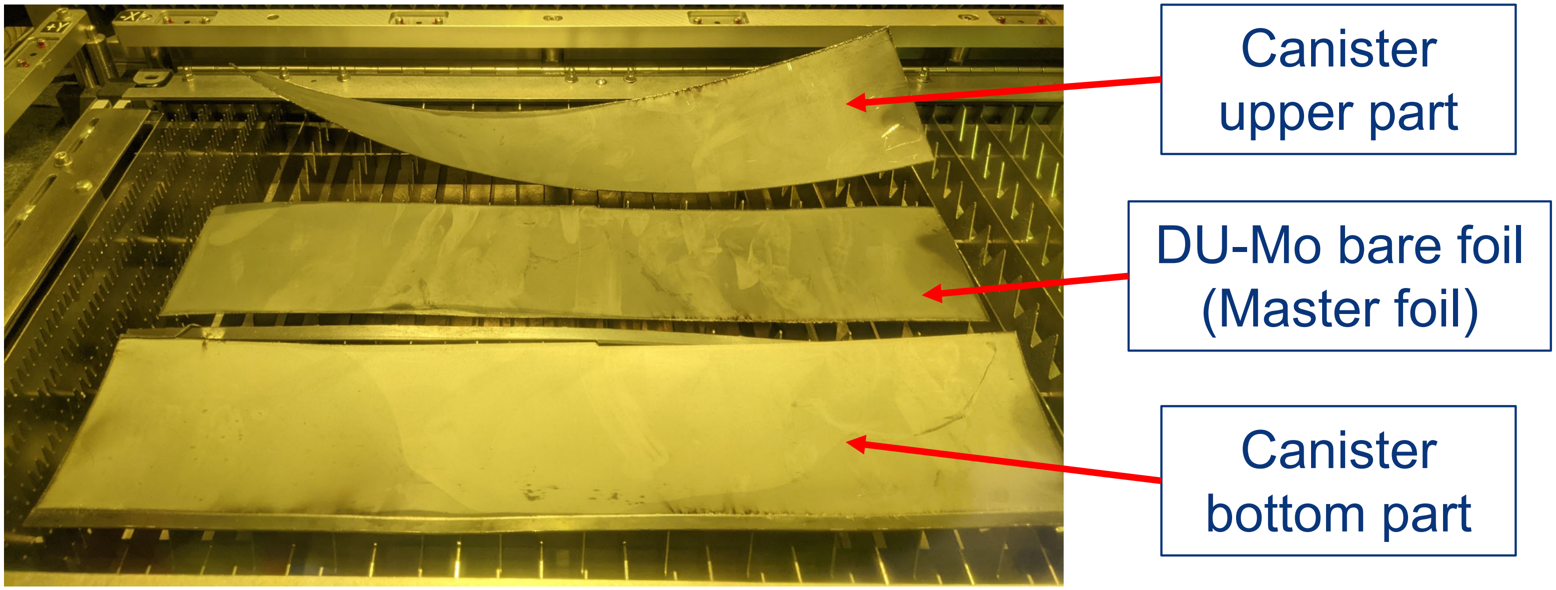


Figure 9: Decaning of U-Mo bare foil after hot rolling

U-Mo flat rolling process

U-Mo bare foil hot rolled laser removed inside glovebox

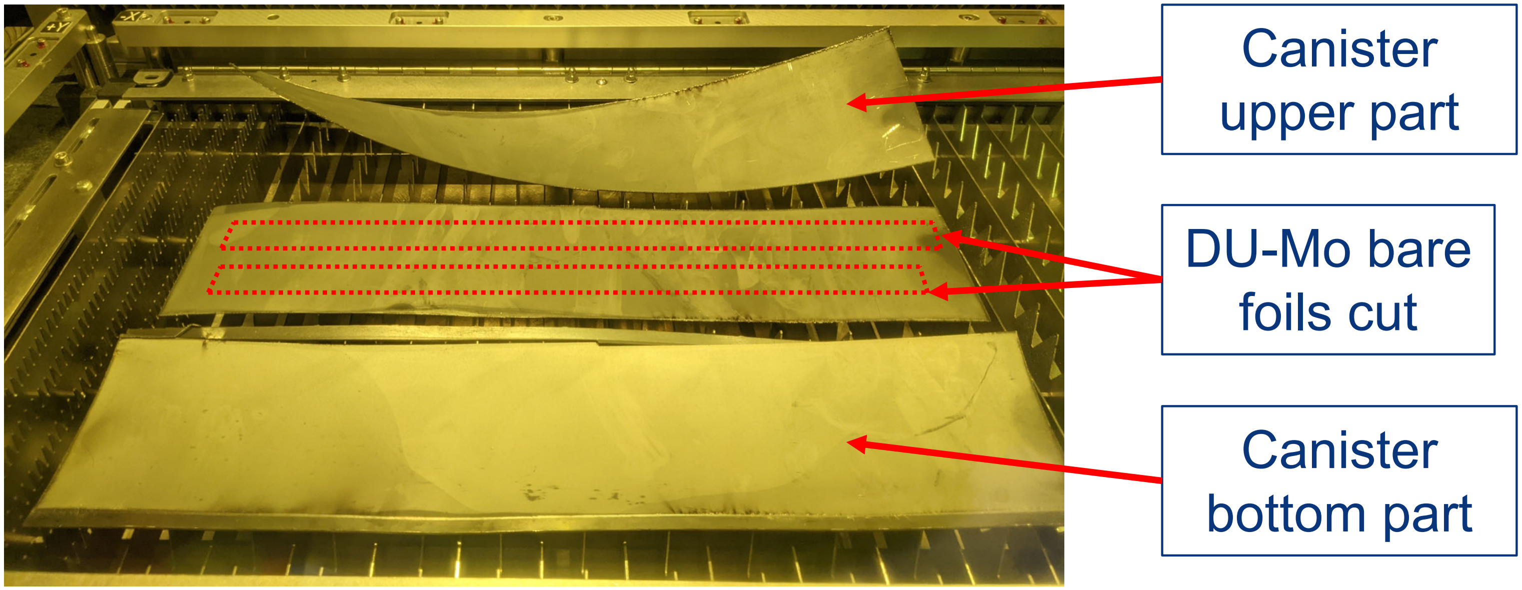
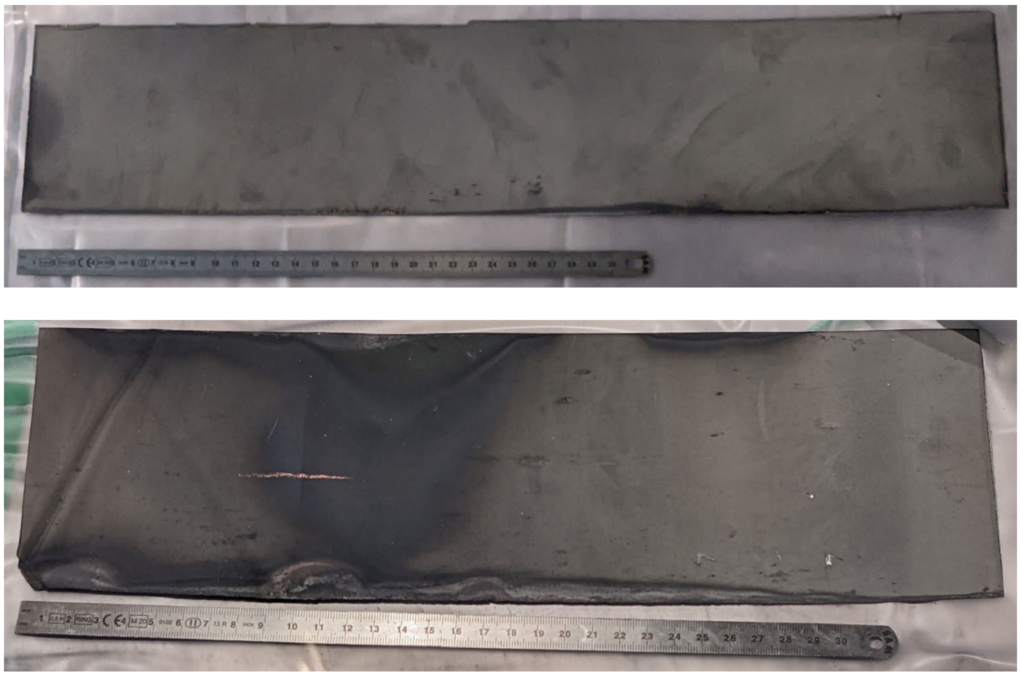


Figure 9: Decaning of U-Mo bare foil after hot rolling

U-Mo flat rolling process

U-Mo bare foil appearance after hot rolling



Foil A

- Length x Width : 550 x 100 mm
- **Thickness : 0.600 mm**

Foil B

- Length x Width : 350 x 100 mm
- **Thickness : 0.850 mm**

Figure 10: Flat rolling step for U-Mo bare foil manufacturing

U-Mo bare foil results

Hot rolling scheme for uranium & inert tests

- Assembly (canister + ingot) thickness reduced to **less than 1.5 mm**
- Working temperature: **650°C**
- **Constant rolling speed** and **load deflection (as RRFM 2021 experiments)** during the overall process

U-Mo bare foil results

Comparison with inert material

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- Working temperature: **650°C**
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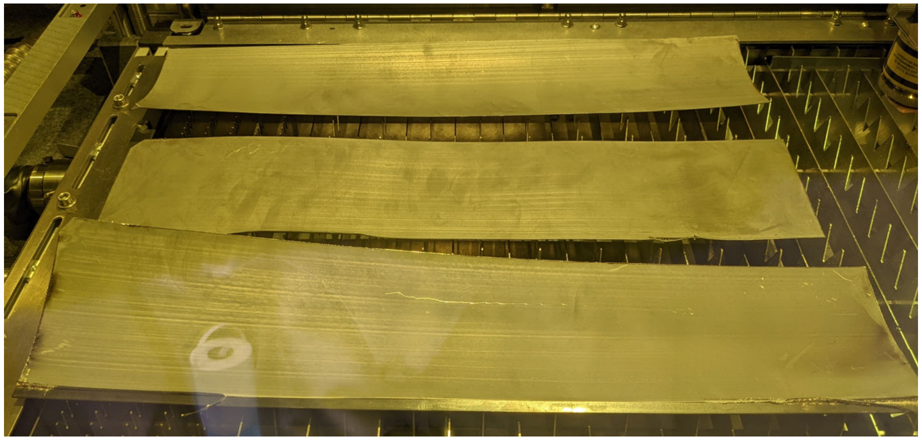

Figure 11: Inert foil decanned by laser cutting

U-Mo bare foil results

Comparison with inert material

- High similarity on loads between inert tests & uranium
- Thickness measured slightly higher for uranium than inert

→ **Hot rolling scheme of inert could be used for depleted uranium alloy**

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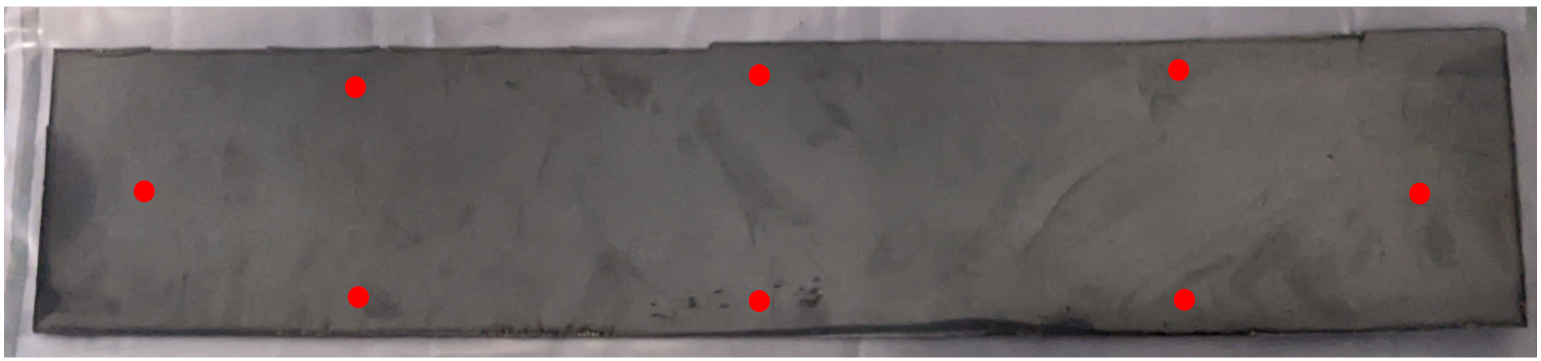
U-Mo bare foil results

Measurement map for both thickness & waviness profile



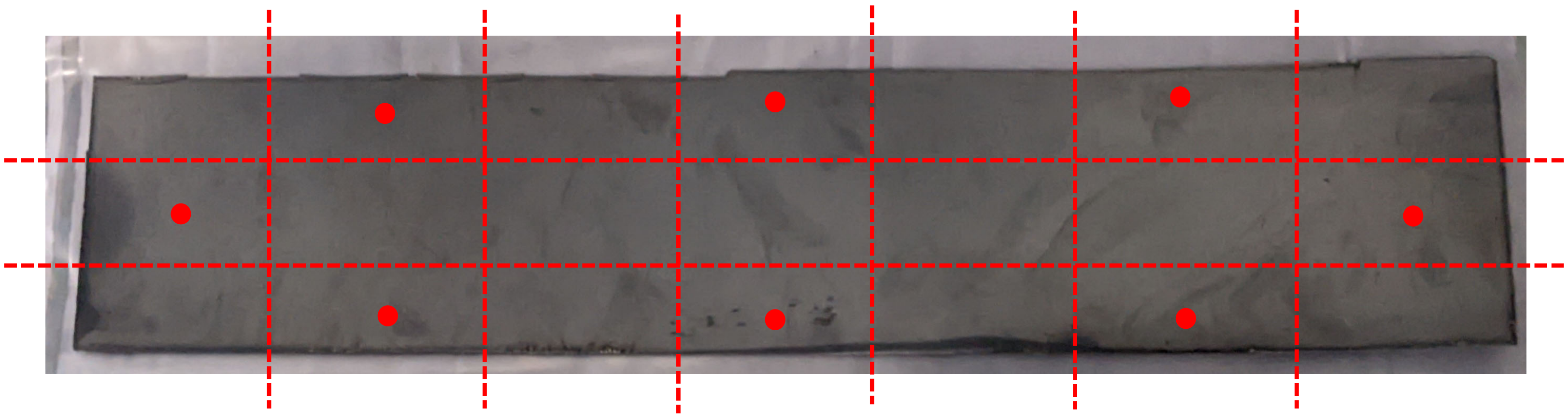
Legend:

● Thickness point measurement

Figure 12: Experimental measurements map for both foil waviness and thickness

U-Mo bare foil results

Measurement map for both thickness & waviness profile



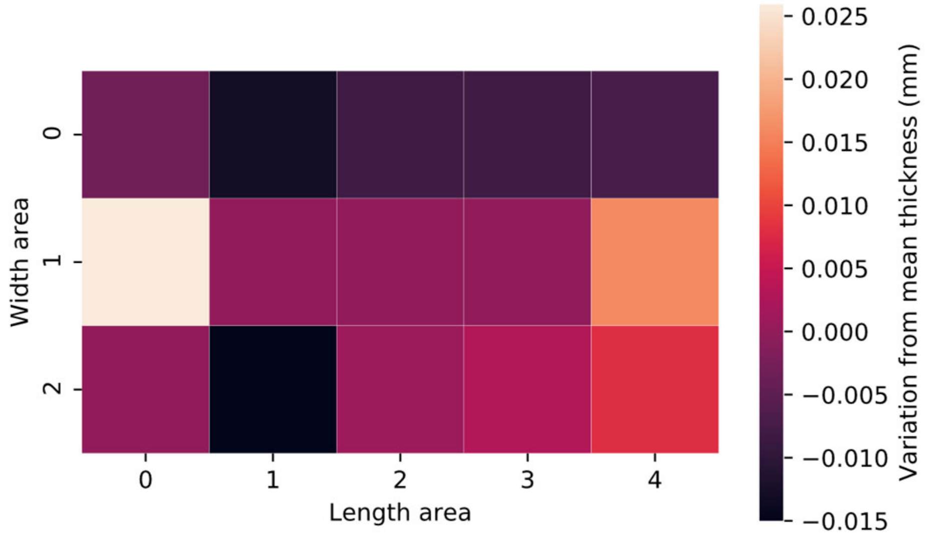
Legend:

- Thickness point measurement
- Area for waviness measurement

Figure 12: Experimental measurements map for both foil waviness and thickness

U-Mo bare foil results

U-Mo bare foil thickness distribution

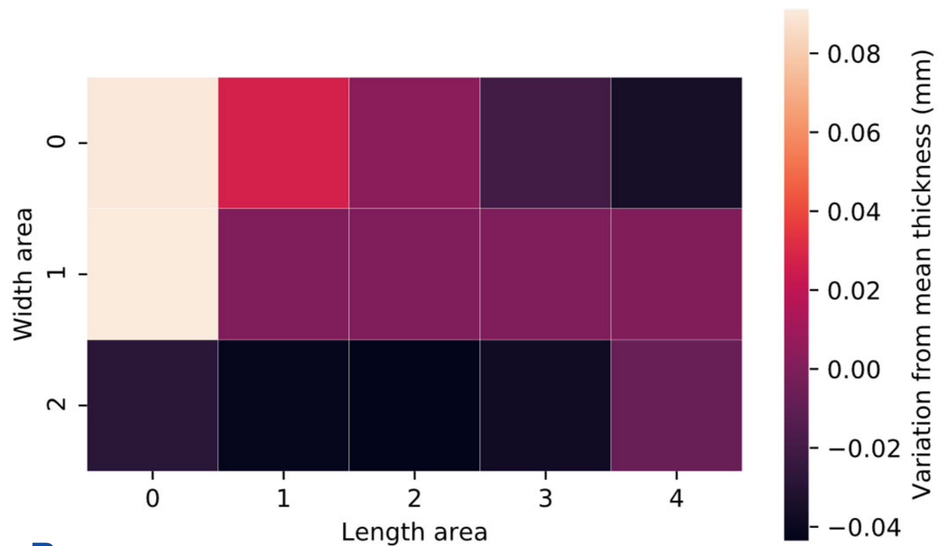


A

Figure 13: U-Mo foil thickness heatmap from thickness mean value

U-Mo bare foil results

U-Mo bare foil thickness distribution



B

Figure 13: U-Mo foil thickness heatmap from thickness mean value

U-Mo bare foil results

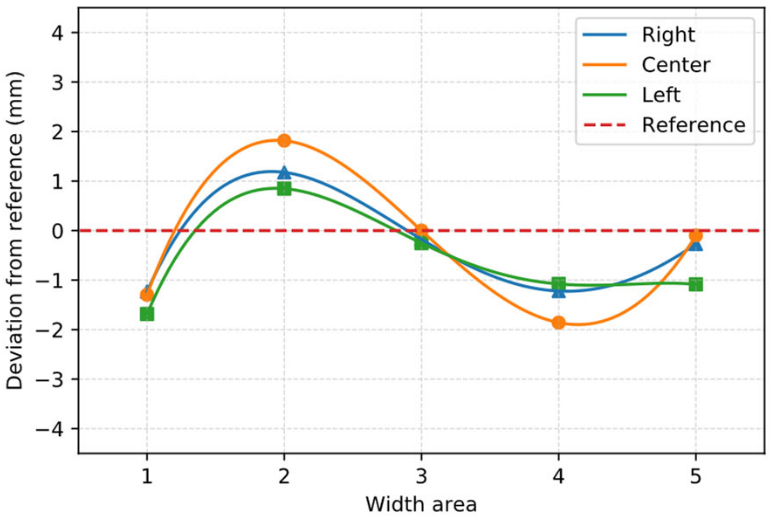
U-Mo bare foil thickness distribution

- Mainly negative variation on edges & positive on center
- Random part variation due to ingot geometry and strength applying

→ **Resolving by cold rolling process to homogenize thickness and by laser cutting of edge parts**

U-Mo bare foil results

U-Mo bare foil waviness profile

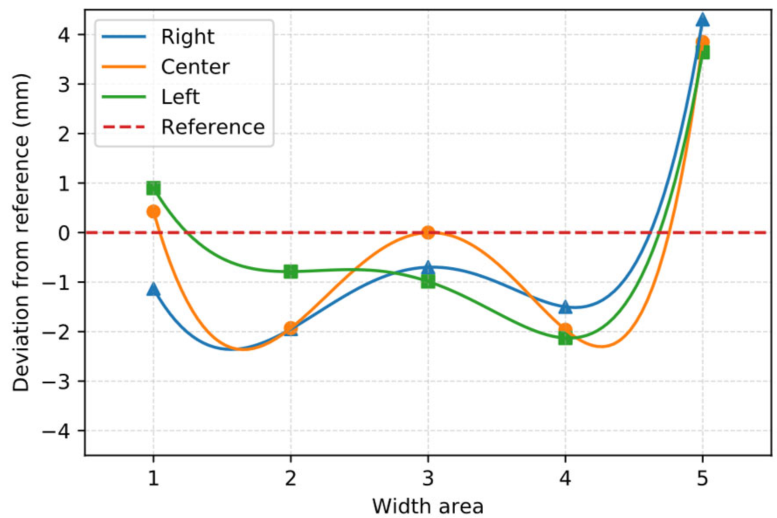


A

Figure 14: Waviness profile for U-Mo foil on different foil sides

U-Mo bare foil results

U-Mo bare foil waviness profile



B

Figure 14: Waviness profile for U-Mo foil on different foil sides

U-Mo bare foil results

U-Mo bare foil waviness profile

- Extremum values on both side of hot rolled foil
- Mostly constant variation from reference between right, middle and left side

→ **Resolving by cold rolling process to improve flatness, heat treatment under loads and laser cutting of both side could resolve theses issues**

U-Mo bare foil results

Global foil quality: thermal gradient

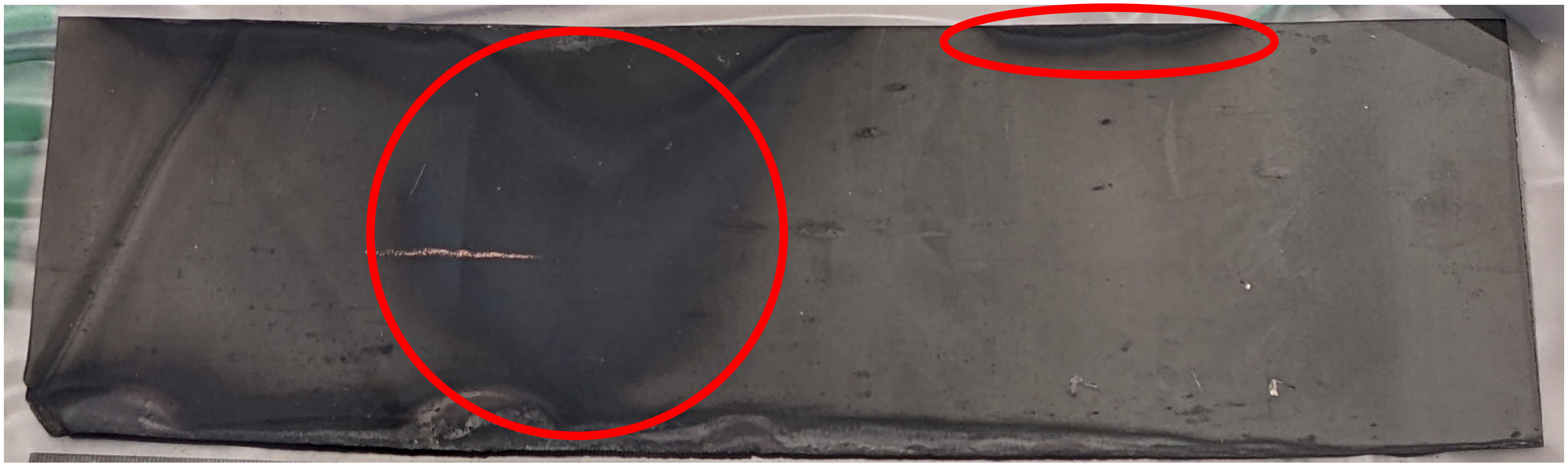


Figure 15: Thermal impact on U-Mo foil after hot rolling

U-Mo bare foil results

Global foil quality: edge cracks

Edge foil cracks

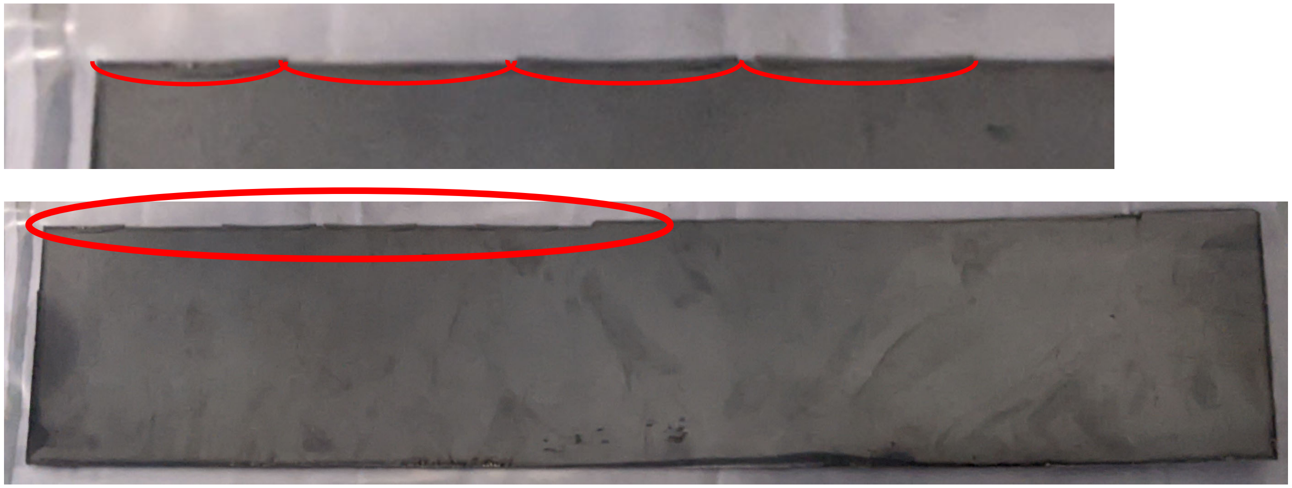


Figure 16: U-Mo bare foil defects after hot rolling process

U-Mo bare foil results

Global foil quality: edge scratches

Edge foil scratches

Figure 16: U-Mo bare foil defects after hot rolling process

U-Mo bare foil results

Global foil quality: edge scratches

- Temperature gradient which affects surface condition (oxide)
- Cracks and scratches on edge foil due to friction, contact with canister, roll strength and mechanical behavior of ingot

→ **Resolving by laser cutting defects after hot rolling & better surface aspect and thickness control of ingot prior to hot rolling**

Conclusions

- Hot rolling mill is implemented and well working in uranium in CERCA laboratory;
- Feasibility of hot rolled U-Mo bare foil in CERCA is demonstrated;
- Global quality of U-Mo bare foil produced will be improved for next manufacturing steps (waviness, thickness distribution, surface condition).

Conclusions

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- Feasibility of hot rolled U-Mo bare foil in CERCA is demonstrated;
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Perspectives

- Hot-rolled foil characterization : microstructure, mechanical & thermal properties;
- Cold rolling process study for bare foil finalization;
- Improving the global process for further industrialization.

Thank You!