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

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

Figure 2: FRM II pool with fuel assembly scheme
FRM II conversion purposes

Fuel conversion

Figure 3: Transverse cut of actual FRM II fuel

\[ \text{U}_3\text{Si}_2 \text{ Plate Highly Enriched Fuel (HEU > 20\% U}_{235} \]
FRM II conversion purposes

Fuel conversion

Figure 3: Transverse cut of actual FRM II fuel

U$_3$Si$_2$ Plate Highly Enriched Fuel (HEU > 20% $\text{U}_{235}$)

Figure 4: New FRM II fuel composition

Aluminum  UMo  Zirconium
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 enrichment U-Mo bare foil production (January 2023 – March 2023)
FRM II conversion purposes

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PVD in FRMII - TUM

C2TWP in CERCA
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**FRM II conversion purposes**

*Focus on for FUTURE-MONO 1 irradiation*

- **Development of U-Mo alloy (2020 - 2021)**
- **Flat rolling U-Mo tests with depleted uranium (May 2022 – December 2022)**
- **Flat rolling inert tests (August 2021 – April 2022)**
- **Lower enrichment U-Mo bare foil production (January 2023 – March 2023)**
- **FUTURE-MONO 1 irradiation (October 2023)**
- **PVD in FRMII - TUM**
- **C2TWP in CERCA**
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

- **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](image-url)
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)
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)

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

RRFM 2021

RRFM 2022

U-Mo coupon

Welding

Lubrified & welded assembly

Hot rolling

Hot rolled assembly

Decanning

Canister

U-Mo bare foil hot rolled (Master foil)
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

- 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

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
U-Mo bare foil results

Measurement map for both thickness & waviness profile

Figure 12: Experimental measurements map for both foil waviness and thickness
U-Mo bare foil results

Measurement map for both thickness & waviness profile

Figure 12: Experimental measurements map for both foil waviness and thickness
U-Mo bare foil results

U-Mo bare foil thickness distribution

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

U-Mo bare foil thickness distribution

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

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

U-Mo bare foil waviness profile

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

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

- Hot rolling mill is implemented and well working in uranium in CERCA laboratory;
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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.
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